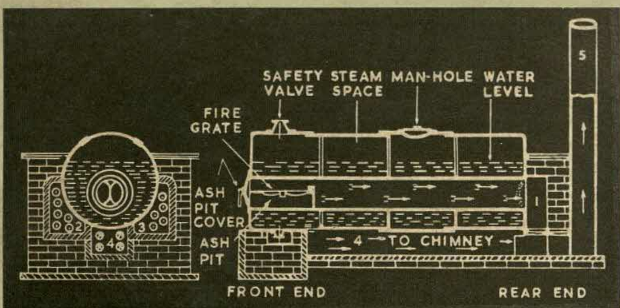
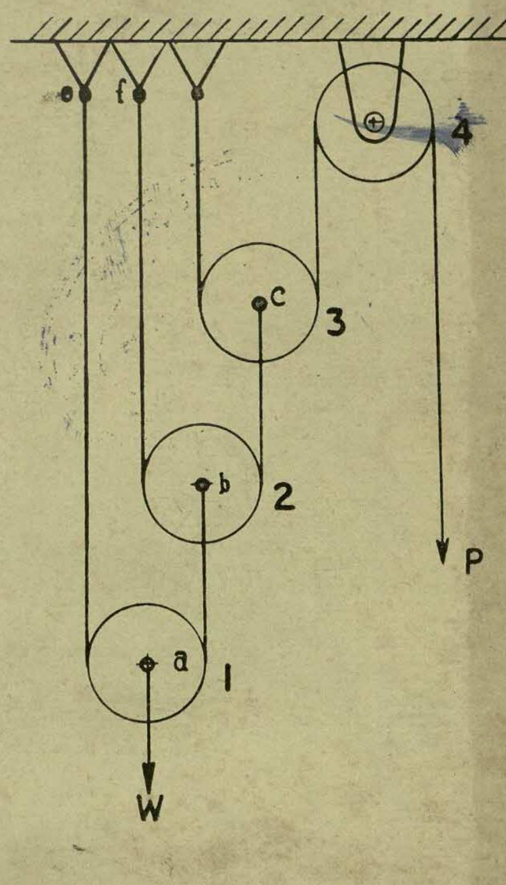
SCHOOL TECHNOLOGY SERIES

ELEMENTS OF MECHANICAL ENGINEERING



A TEXTBOOK
FOR TECHNICAL SCHOOLS

NATIONAL COUNCIL
OF EDUCATIONAL RESEARCH
AND TRAINING



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MECHANICAL ENGINEERING

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A TEXTBOOK FOR TECHNICAL SCHOOLS

S. K. BASU

NATIONAL COUNCIL OF EDUCATIONAL RESEARCH AND TRAINING

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Foreword

IT is a truism that we live in an age of technology. Our four successive Five Year Plans are all directed towards the development of a technological society. To this end, we have to train a multitude of technicians who will set up plants, and design and produce machines, tools and implements to bring to fruition the well-considered Plans of an informed leadership.

The National Council of Educational Research and Training is particularly concerned today with education at school level. Technology is one of the fifteen subject-fields in which the National Council, on the advice of its Central Committee on Educational Literature, is bringing out textbooks. In agreement with public feeling and recent recommendations of the Education Commission report, the Council is producing educational materials for vocationalized secondary schools. The present publication on mechanical engineering is an earnest of its plan of work to provide the schools with model textbooks. This is one of the four textbooks that have been prepared under the direction of Prof. K. B. Menon, Head of the Department of Electrical Engineering, Indian Institute of Technology, Kharagpur. *Engineering Drawing* and Elements of *Electrical Engineering* have been published. *Workshop Practice* is now in press and will be released shortly.

Elements of Mechanical Engineering is an introductory book for students in the higher classes of Indian secondary schools, who offer engineering as an elective subject and for students of specialized technical schools. The book will also be useful in the earlier stages of the polytechnic diploma course. The aim of the book is to present an over-all view of the major areas in the subject without entering into specialized details required for advanced studies. Its purpose is to develop in the students an understanding of the basic principles of mechanical engineering. The text is in simple English and all technical terms have been defined with clarity.

The National Council wishes to thank the author of the book, Dr. S. K. Basu, for having undertaken this work, and Prof. K. B. Menon who has directed the whole project of textbooks in technology. The Council is also grateful to Dr. S. R. Sen Gupta,

Director, Indian Institute of Technology, Kharagpur, for the facilities provided for the completion of the project.

The National Council hopes that all students of technology at secondary level and students of specialized schools and polytechnics will benefit from this book. Suggestions from teachers and others interested in mechanical engineering are welcome and will be considered when the book is revised.

L. S. CHANDRAKANT

Preface

THIS book deals with the fundamental principles of mechanical engineering and has been written to create in the minds of the young learners at the higher secondary level a lively interest in engineering. It has been written according to the syllabus of the higher secondary technical stream which covers the basic ideas of the broad field of mechanical engineering.

Care has been taken to present the matter in a simple and lucid manner with the help of sketches and illustrations wherever needed. For the benefit of the students undergoing the course, quite a few numerical problems have been solved in each chapter. Further, a list of questions has been added at the end of each chapter with a view to making the students familiar with typical problems.

Though the book is primarily meant for technical students of higher secondary schools, it is expected that it will be a valuable guide to students taking a diploma course in Mechanical Engineering.

I am indebted to Dr. S. K. Sen and Prof. S. C. Das of I. I. T., Kharagpur, for editing the language and reading the book in typescript respectively, and for offering valuable comments and suggestions. I also received considerable help from Shri A. K. Sen and Prof. S. N. Sengupta of R. E. College, Durgapur, in writing two chapters.

I also thank Shri M. P. Roy for the pains he took in typing the matter over and over again, and Shri S. K. Dhar and Shri K. D. Ganguly, for drawing and redrawing the sketches.

S. K. BASU

Contents

CHAPTER 1

Force: graphical composition and resolution of forces; triangle, parallelogram and polygon of forces and their applications; moments, friction and lubrication.

1.1 Introduction

What happens to a body when a force or a number of forces act on it, is the concern of 'mechanics'. How the force affects the body is governed by certain basic laws which are the 'laws of mechanics'. It is the first task of a mechanical engineer to know these laws. Take the case of a simple mechanical device, an electric fan. A layman knows what this fan does. It keeps the room cool. But a mechanical engineer knows how this fan has been designed and how some of the mechanical laws have been applied here. All around us we find such devices which have made our life easy and comfortable. These are skilful applications of certain mechanical laws. If we closely observe some of the natural phenomena, for instance, the movements of wind or water, we shall find that they too obey certain mechanical laws. The forces working behind them are gravitational attraction, atmospheric pressure, etc. Let us start our enquiry with the term 'force'.

1.2 Force—Its Nature and Measurement

A body in a state of rest prefers to stay so; this is known as its state of inertia. Any action to change this state of rest to one of motion is resisted. What causes the body to change this state of inertia is a 'force'. A body in a state of uniform motion would prefer to stay so; this also is its state of inertia. And the body would resist any action, i.e., any 'force', which would tend to change its state of uniform motion to one of rest. Thus we may define 'force' as some action which changes or tends to change the state of rest or the state of uniform motion of a body. We apply force to lift a load, to move a vehicle or to stop a running vehicle. In some cases more than one force may act on a body in such a manner that the resultant force is nil. Take, for example, the case of a pot resting on a table. There is a force acting on it vertically down; this is known as 'gravitational force' which is equal to the weight of the pot. This is resisted by another force exerted by the table. The latter is equal and opposite to the former and the two cancel each other. Hence the pot rests on the table. Here the two forces are said to be in equilibrium.

A force is measured by the amount of change it brings about in the total quantity of motion of a given body in a given time. The quantity of motion, i.e., momentum, is defined as the product of mass and velocity. A body having a certain mass and moving with a certain velocity will possess the same momentum as that of a body with double the mass and moving with half the velocity. The magnitude of a force is measured by the change of momentum caused to a given body in a given time.

1.3 Force is a Vector Quantity

To know a force fully it is not enough to know its magnitude. A force has also a specific direction. In technical language a force is a 'vector quantity'. A 'vector quantity' has a

magnitude as well as a specific direction, while a 'scalar quantity' has only magnitude but no direction. 'Speed' and 'velocity' will illustrate this distinction. In terms of magnitude, i.e., distance moved per unit time, speed and velocity are the same; but there is a difference between the two when we consider direction. Speed has no direction while velocity has a specific direction. Thus we say that velocity is a 'vector quantity' and speed is a 'scalar quantity'. Force is also a vector quantity. When we consider a rigid body acted upon by a force we should also consider another element of force, namely, its point of application. If a force acting on a body tries to pull it apart or stretch it, the force is known as a tensile force. When a force acting on a body tries to compress the body it is known as a compressive force. To define a force completely we must know its (1) magnitude, (2) direction, (3) point of application and (4) sense. (The sense of the force relates to its tensile or compressive nature.)

The common units for measuring the magnitude of force are 'kilogramme weight' or simply 'kilogramme' or kg in the metric system, and 'pound weight' or simply 'pound' (written as lb.) in the FPS system.

1.4 Laws of Motion

The science of mechanics centres round the three Laws of Motion which are known as Newton's Laws of Motion. These can be expressed in the following manner.

FIRST LAW—*When a body is at rest or in a state of uniform motion it has a tendency to remain at that particular state until and unless it is acted upon by an externally applied force.*

SECOND LAW—*The rate of change of momentum is proportional to the impressed force and takes place in the direction in which the force acts.*

THIRD LAW—*To every action there is an equal and opposite reaction.*

The second law may require some explanation. When a body of mass moves with an acceleration f (acceleration is the rate of change of velocity or change of velocity per unit time), the force P acting on it can be mathematically given in the form P = K.m.f., where K = constant. K can be made equal to 1 by choosing a suitable unit system.

We know that the product of mass and velocity is termed momentum. Since the mass of a body is normally constant, the change of momentum = mass × change of velocity.

Rate of change
of momentum = K × mass × (rate of change of velocity)
= K × mass × (change of velocity per unit time)
= K × mass × acceleration
= K × m × f = P, where K = Constant = 1 for suitably chosen unit, and P is the externally applied force.)

We shall have a more clear understanding of these laws and their implications, while solving practical problems of mechanics, discussed later.

1.5 Resolution and Composition of Forces by Graphical Analysis

Since force is basically a vector quantity with a sense and point of application, it can be represented by a directed straight line, as shown in Fig. 1.1. In Fig. 1.1, the length of the straight line OA denotes the magnitude of the force P, and O is the point of application of the force on the body. The direction of the force is indicated by the arrowhead from O to A. Such a force will obviously try to move the body in the direction indicated by OA. For a complete identification of the force we should represent it in the form P indicating that it is a vector quantity of magnitude P.

To keep the above body in equilibrium, there should be another force Q of the same magnitude acting on the body in the direction OB opposite to the direction OA.

Parallelogram of Forces. If two or more forces act on a body and a single force be found whose effect on the body is the same as the combined effect of the two or more forces, this single force is termed as the resultant force.

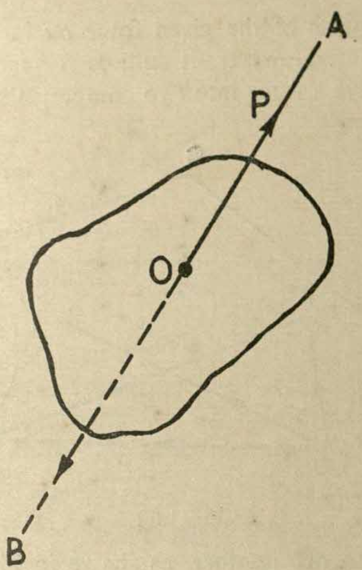


Fig. 1.1

Let the two forces $\vec{P}$ and $\vec{Q}$ act on a body at the point of application O and be represented in direction and magnitude by OA and OB, as in Fig. 1.2. To get the resultant of these two forces we should draw the parallelogram OACB which is called the 'Parallelogram of Forces.' In this case the resultant of the two forces $\vec{P}$ and $\vec{Q}$ will be given in direction and magnitude by the diagonal of the parallelogram OC. Let us term this resultant as $\vec{R}$, acting in the direction O to C.

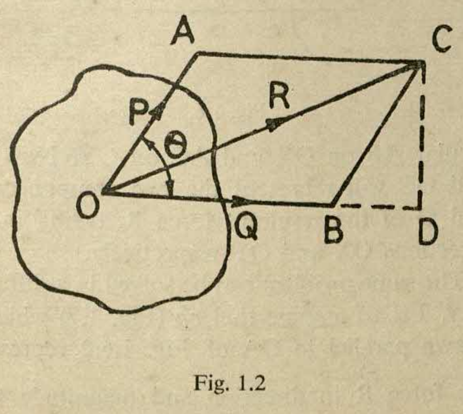


Fig. 1.2

Let us now take a slightly complicated case shown in Fig. 1.3, where a third force S is acting on the body at the same point of application. In such a case we shall have to combine with $\vec{R}$, to get the resultant by drawing parallelogram of forces in the same way. If S is represented by OD in magnitude and direction, then we shall construct a second parallelogram OCED, whose diagonal OE will represent the resultant of the three forces $\vec{P}$, $\vec{Q}$ and $\vec{S}$, in

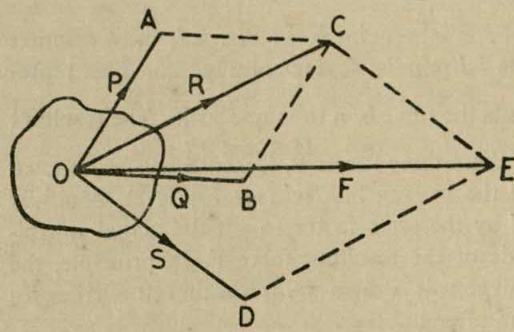


Fig. 1.3

direction and magnitude. This is known as addition or composition of forces.

The same result could be obtained in a simpler way by using a triangle of forces or polygon of forces. Let us see how this method is different from the previous one. Let us draw a line *oa* parallel to OA to represent the force P in a certain scale. From the point *a* draw a line *ab* parallel to OB to represent the force Q, in direction and magnitude in the same scale. Join *ob* which represents the resultant R of the forces $\vec{P}$ and $\vec{Q}$. To get the actual magnitude $\vec{R}$ we must multiply *ob* by the scale factor. This is called the graphical method of composition by triangle of forces. The direction of R is represented by *ob*, as shown in Fig. 1.4. Comparing Fig. 1.4.1 and Fig. 1.2, we see that the triangle is actually half of the parallelogram we had previously drawn in Fig. 1.2.

The composition of three forces acting at the same point of application can be arrived at graphically in a similar way.

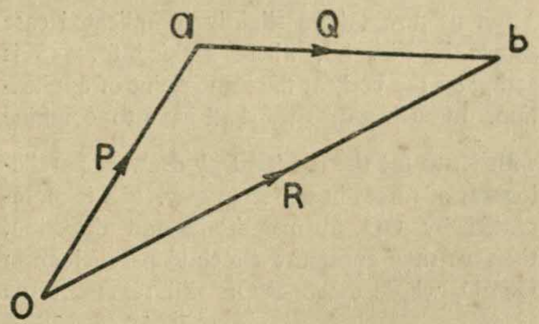


Fig. 1.4

From the point b, in Fig. 1.5, draw another line bd parallel to OD of Fig. 1.3. This represents the force $\vec{S}$ in the same scale. The resultant of these three forces $\vec{P}$, $\vec{Q}$ and $\vec{S}$ will be denoted by the closing link od (*see* Fig. 1.5). Multiply od by the scale factor to get the actual magnitude of the resultant force F. In principle, the polygon is drawn by repeating the triangles one after another.

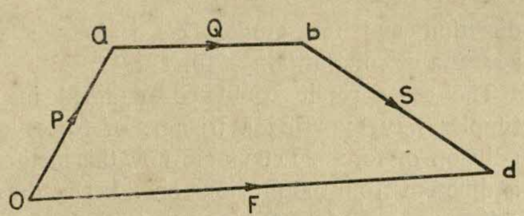


Fig. 1.5

In this way by constructing the polygon of forces, we can combine any number of forces acting at the same point on a body.

Similarly, for a given force we can find out a system of forces whose combined effects are the same as that of the given force acting alone. This is known as resolution of forces. The forces in the equivalent system are called the components.

A force acting on a body can be resolved into components in desired directions by the graphical method, as shown in Fig. 1.6.1. The force oa is equivalent to the forces $\vec{ob} + \vec{ba}$ or $\vec{oc} + \vec{ca}$ or $\vec{od} + \vec{de} + \vec{ef} + \vec{fa}$, which may be the components of the given force oa in different directions. However, it suffices for most cases to resolve a force into two components at right

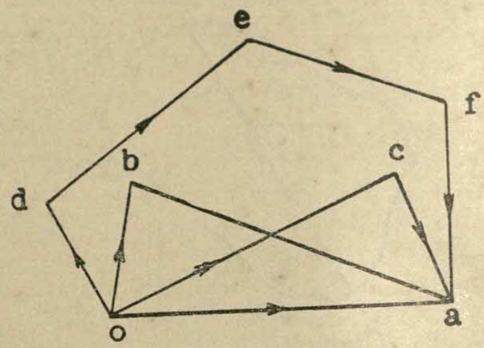


Fig. 1.6.1

angles to one another, as shown in Fig. 1.6.2. Let us assume that there is a force R acting on a body at a point of application O and its direction is shown by OA. Suppose we want to resolve it into two components acting in the direction OX and OY, which are perpendicular to each other. We can solve this problem in two ways. In the first method, drop a perpendicular AB on OX and AC on OY. Now OB and OC will represent the two components P and Q of the resultant force R, acting in the directions OX and OY respectively.

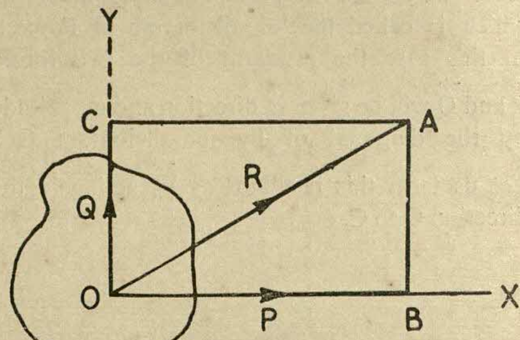


Fig. 1.6.2

The same problem can be solved in a different way. Let us assume that oa (Fig. 1.7) which is drawn parallel to OA of Fig. 1.6.2 represents the force $\vec{R}$ in direction and magnitude to a

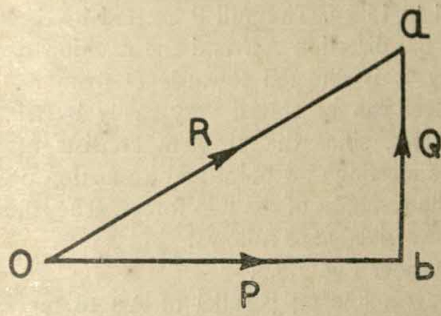


Fig. 1.7

certain scale. Through a draw a line parallel to OY and through O draw a line parallel to OX. Let these two lines intersect at b. Then ob and ba will represent the forces $\vec{P}$ and $\vec{Q}$ in direction and magnitude in the scale chosen. To get the actual value of $\vec{P}$ and $\vec{Q}$, we must multiply ob and ba respectively by the scale factor. If the direction of the force R is represented by arrowhead moving along o to a, then the directions of the two resolved components of $\vec{R}$ can be found out as follows: Suppose our objective is to move from the point o to the point a. When we move through the minimum distance we get the direction of the resultant force. But if we go to a by a roundabout way, that is, we first move from o to b and then from b to a we get the directions of the two resolved components of $\vec{R}$; the direction of $\vec{P}$ will be from O to b, while the force $\vec{Q}$ will be directed from b to a. This simple convention for finding out the directions will be used in all cases of solution by a triangle of forces or polygon of forces. Regarding the magnitude of the forces it is comparatively easier to understand that if oa represents the magnitude of the force $\vec{R}$ to a certain scale, then ob and ba will represent the magnitude of the forces $\vec{P}$ and $\vec{Q}$ in the same scale.

For a clear understanding, it is necessary for a student to solve some numerical problems. Let us now take a few practical problems, where the solution of the forces can be obtained by

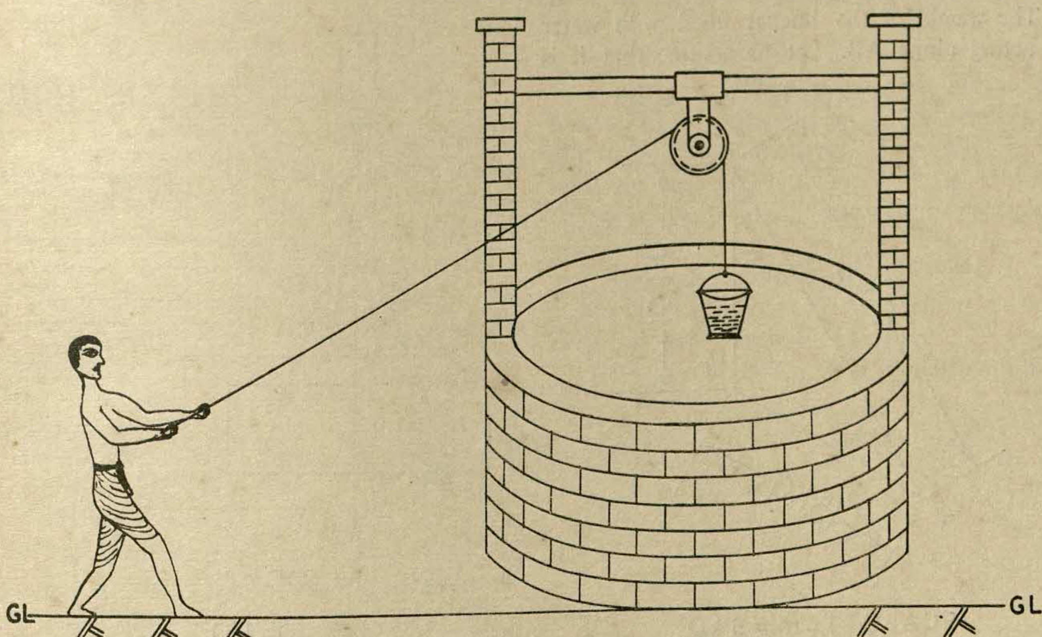


Fig. 1.8.1

actually drawing the triangle or the polygon of forces.

In the example shown in Fig. 1.8.1, a man is drawing water in a bucket from a well. The bucket is held at one end of the rope passing over the hanging pulley, while the man pulls the rope at the other end. Suppose we want to find out the total force acting at the centre of the pulley. The problem can be represented as below in Fig. 1.8.2.

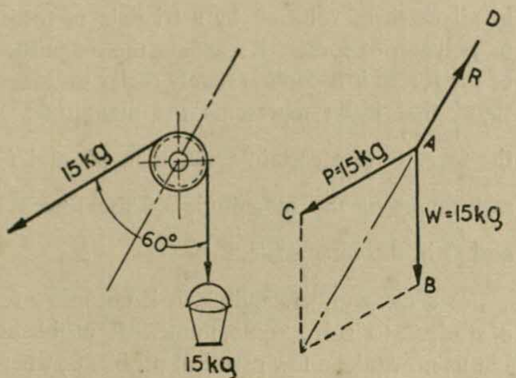


Fig. 1.8.2

The weight of the bucket filled with water is acting along AB. Let us assume that it is

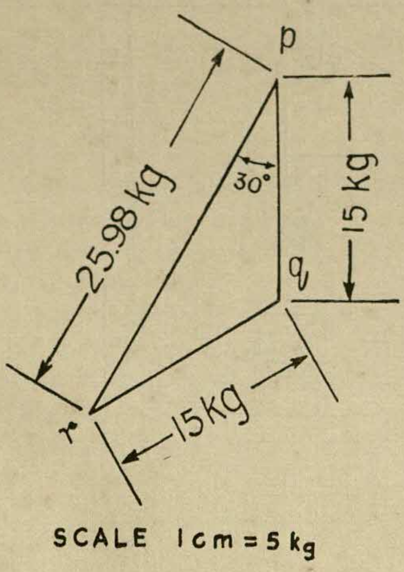


Fig. 1.8.3

equal to 15 kg. The pull P exerted by the man is in the direction AC and the reaction on the pulley R is directed towards D from A. The problem can be solved very easily by triangle of forces, since the problem consists of two forces meeting at a point and a reaction opposing the resultant of the two forces. The solution can be arrived at as follows:

Consider Fig. 1.8.3.

Draw a line pq parallel to AB to represent $W = 15$ kg to a certain scale, say, 1 cm $= 5$ kg. From q draw a line qr parallel to AC equal to pq, i.e., 15 kg. Join pr which will represent the resultant in direction and magnitude. Measure pr and multiply it by the scale-factor to get the magnitude of the resultant R. The measured value will be: $R = 25.98$ kg

The direction of the reaction R will be at an angle 30° to the vertical and away from the centre of the pulley.

Fig. 1.9.1 shows the method of hanging a weight to be transported by an overhead travelling crane. The weight is tied by two loops of a rope hanging from the crane hook.

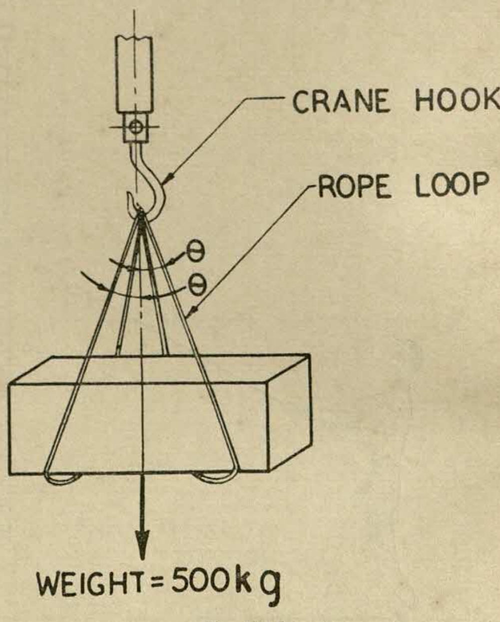


Fig. 1.9.1

Fig. 1.9.2 gives a simplified diagram for the purpose of calculation. OC represents the

reaction acting vertically up along the axis of the crane hook, OA and OB represent the forces on the two loops of the rope, each making an angle O with vertical. At first sight it would seem that each of the loops will take half of the load lifted, since there are two loops supporting it, but in actual practice it is different. In fact the load on each loop of rope will be more than 500/2 kg.

Solution of such a problem can be done graphically, since the system consists of two forces and a reaction meeting at a common point. Let us draw the triangle of force (Fig. 1.9.3) in a particular scale (say, 1 cm=50 kg). Draw a line pq of length 10 cm vertically (parallel to OC) to represent the reaction R=500 kg. From q draw a line parallel to OA and from p draw a line parallel to OB. Let these two lines meet at a point r. The magnitude of the force acting in OA will be given by qr multiplied by the scale factor, while the magnitude of the force acting along OB will be obtained by rp duly multiplied by the scale factor. The directions of the forces will be as shown by the arrowheads. In Fig. 1.9.3 the angle pqr=θ, $\angle$rpq=θ. Therefore the angle qrp=180 — 2θ.

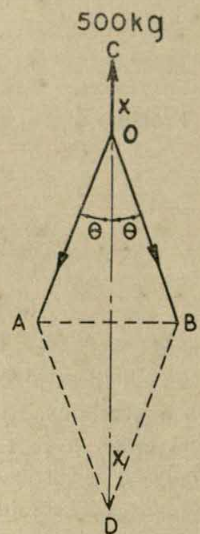


Fig. 1.9.2

If now the two loops are gradually brought nearer to the vertical axis (*see* Fig. 1.9.2), the angle θ decreases. As θ decreases, the point r in Fig. 1.9.3 will gradually come nearer and nearer to the line qp. Ultimately when θ will be equal to zero, the point r will be on the line qp and qr+rq will be equal to pq. But for all values of angle θ, pr = rq. Therefore we can say that pr=rq =pq/2. It shows that each of the loops will take half of the load, when θ=O.

If the angle θ becomes 90°, that is, the loops OA and OB are horizontal, then the line pr

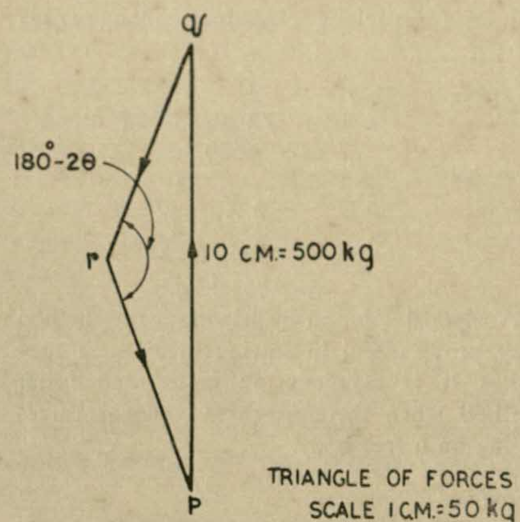


Fig. 1.9.3

and qr will run parallel and horizontal from the point p and q respectively. In such circumstances we say that the load on OA and OB (*see* Fig. 1.9.2) will be infinitely large. Usually the angle θ should be more than o° but less than 90°. In actual practice θ should be less than 60°.

Analytically also, the problem can be solved by constructing the parallelogram of the two forces OBDA representing the two forces by OA and OB respectively. Since OC represents the reaction, it is equal to the diagonal OD of the parallelogram in magnitude (opposite in direction).

Thus we can say that OD=500 kg.

But OD= projection OA on the axis x x + projection of AD on the axis xx

= Projection on x x of OA + projection on x x of OB

= OA Cos θ + OB Cos θ = 2 × OA × Cos θ.

Since OA and OB are equal,

Therefore $\text{OA} = \dfrac{500}{2 \text{ Cos } \theta}$

and $\text{OB} = \dfrac{500}{2 \text{ Cos } \theta}$.

If θ=60°, Cos 60°=1/2 and

we get force along OA=force along OB= 500 kg.

If $\theta=45°$, Cos $45°=\frac{1}{\sqrt{2}}$ and hence along

$$OA=\text{force along } OB=\frac{500}{2\times\frac{1}{\sqrt{2}}}$$
$$=500\times0.707$$
$$=353.5 \text{ kg.}$$

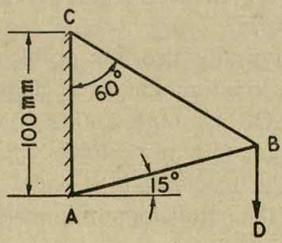
Analytical solution by trigonometric method may prove useful in solving many such problems. It is definitely an easier and faster method when there are three coplanar forces acting on a free body.

PROBLEMS

1. In the figure given below is shown a boom AB carrying a load of 2500 kg at the end B. The boom is supported by an additional cord BC fixed from the wall. If the distance between C and A is equal to 100 mm, find out graphically the nature and magnitude of the force acting along AB and BC.

(*Answer* : 3062 kg and 3414.5 kg)

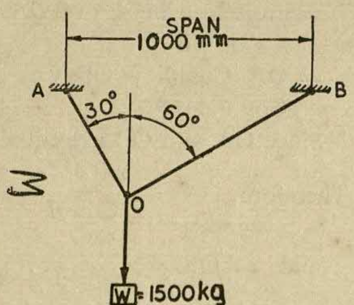
Problem I



2. A load of 1500 kg is supported by two cords fixed on the ceiling of a room at points 1000 mm, as shown in the figure below. Find out graphically or otherwise the forces on the cords OA and OB.

(*Answer* : 1299 kg and 750 kg)

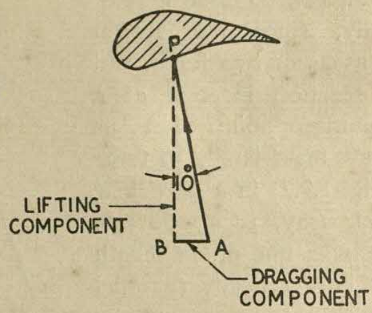
Problem 2



3. A normal force P=2500 kg is acting on the section of an aerofoil in the direction AP making an angle of 10° with the vertical plane. Find out graphically or otherwise the lifting and dragging components resulting therefrom.

(*Answer* : 2462 kg and 434 kg)

Problem 3



In all these problems, the forces are acting on a free body. By free body analysis we mean that either a part or the entire body can be analysed as distinct and separate from its surrounding. The solutions of such problems will prove easier if we first draw the sketch of the free body mechanism to a scale. Teachers are, therefore, particularly advised to instruct the students to develop an ability to draw the free body problems first before trying any solution. For many complicated problems on free body, the result may be obtained quicker in the graphical way rather than by any other analytical method. Moreover, engineers should be well versed in solving graphically as far as practicable, for economising time.

We have so far confined our discussion only to free body problems acted upon by coplanar and concurrent forces. By this we mean that in the problems discussed so far, we have dealt with forces acting in the same plane and having their line of actions passing through a common point.

1.6 Moment of a Force

Moment of a force about a point can be defined as the product of the force and the

normal distance of the point from the line of application of the force. This normal or perpendicular distance is known as the 'arm' of the force, while the point is known as the centre of moment.

Let us assume that in Fig. 1.10, A is the point of application of the force P and O is the point about which the moment of the force P is to be found out. From O drop a perpendicular OA on the line of application of the force (=PA). If OA is denoted by X, then the moment of the force P about O will be algebraically written as $M_o = P\ X$, where M_o denotes the moment of the force about point O.

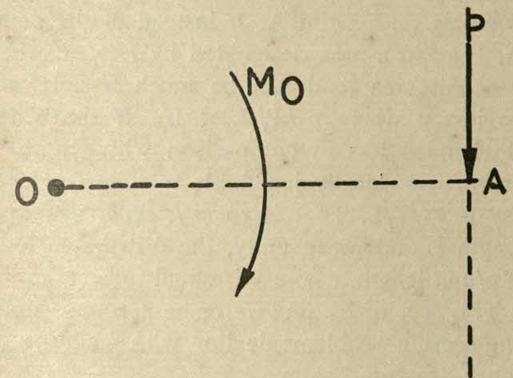


Fig. 1.10

Moment, like force, is a vector quantity, since it has magnitude as well as direction. In this figure the force P will produce a clockwise moment about O as shown by arrow. This can be well understood by considering the tendency of rotation of the line OA about O under the effect of the load P. Let us assume that the clockwise moment as in Fig. 1.11 is positive, then the counter clockwise moment should be regarded as negative.

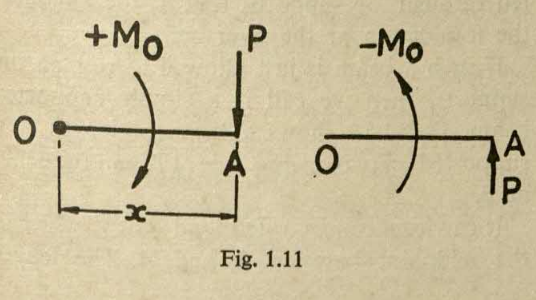


Fig. 1.11

It should be remembered that the moment of a force with respect to a point is the same as the moment of the force with respect to an axis passing through the point normal to the plane through the force and the point.

Since the moment is a product of force and distance, the unit of moment will be kg/m (kilogram metres) or kg/mm (kilogram millimetres).

If two parallel forces of equal magnitude but opposite in direction act on a body, then they are said to be producing what is known as a couple. A couple can be measured by multiplying the force with the normal or minimum distance between the two aforesaid parallel forces.

Since the moment of the force P about the point O is equal to $M_o = P\ X$, it follows that when $X = 0$, that is O coincides with A, M_o is also zero. That is to say, the moment of the force about its point of application or about any point on the plane passing through the point of application parallel to the direction of the force, is equal to zero.

Let us take a case shown in Fig. 1.12, in which there are two forces $\vec{P}$ and $\vec{Q}$ denoted by AB and AC making an angle β and α respectively

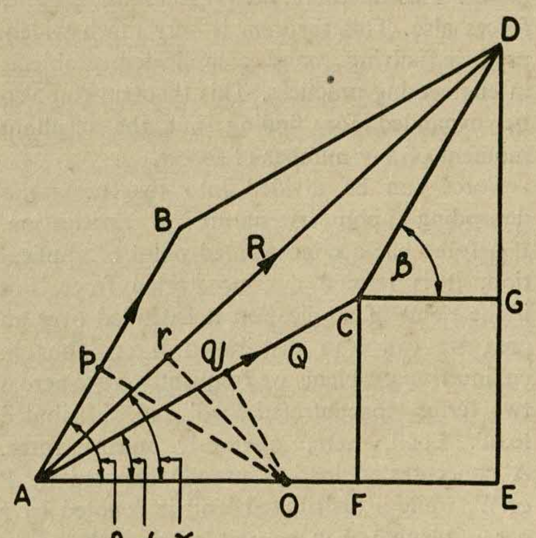


Fig. 1.12

with the line AE. These two are intersecting forces meeting at A and lying in the same plane. Let us complete the parallelogram of forces BACD, the diagonal AD will denote the resultant R of the two intersecting coplanar forces $\vec{P}$ and $\vec{Q}$. Let γ be the angle that the resultant makes with AE. In finding out the moment of these forces about any point O in the plane, we drop perpendicular Op_o. Oq and *or* on AB, AC and AD.

$$M_o = [\vec{P} \times Op + \vec{Q} \times oq]$$
$$= [AB \times op + Ac \times oq]$$
$$= [AB \times A_o \sin\beta + AC \times A_o \sin\alpha]$$

Since $OP = AO. \sin\beta$ and $oq = A_o. \sin\alpha$

$$\therefore M_o = A_o. [AB \sin\beta + AC \sin\alpha]$$
$$= AO. [CD \sin\beta + CF]$$
$$= AO\,[GD + GE] = AO\,[ED\,6]$$
$$= AO \times AD \sin\gamma = R \times A_o \sin\gamma$$
$$= \vec{R} \times Or$$

Therefore $M_o = \vec{P} \times Op + \vec{Q} \times oq = \vec{R} \times Or.$

Algebraic sum of the moments of the coplanar concurrent forces about any point lying in the same plane is equal to the moment of the resultant of the forces about the same point. This is known as Varignon's theorem of moments. This theorem holds good for parallel forces also. This theorem is very much widely used in solving many complicated problems in engineering practices. This theorem can also be expanded for finding out the resultant moment of any number of forces.

Force can be divided into two categories depending upon its nature of application. If a force has a concentrated point of application, it is termed a concentrated force. But if the point of application is extended over an area we call it a distributed force. Thus in engineering problems we frequently come across two terms 'concentrated load' and 'distributed load'. Load, here, obviously means force. A concentrated load is usually denoted by P or W, while a distributed load is denoted by P per unit length or W per unit length of the beam. Let us now refer to the Fig. 1.13 showing the conditions of loading.

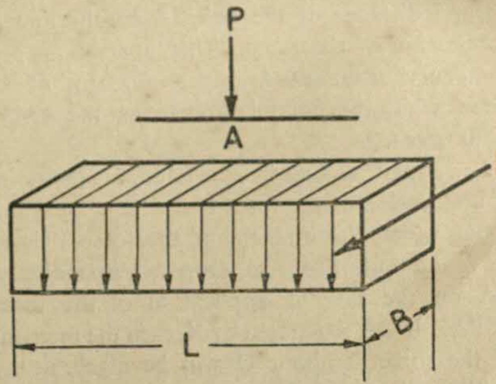


Fig. 1.13

In the first case the total load or force P is acting on a point A. If instead of the point A, P acts on area designated by L × B, then per unit area load will be much less. It will be just p where $p = P/(L \times B)$. If the width B is much less in comparison with length L and if it is ideally justifiable to take $B = 1$ we say $p = P/L$. That is to say, on a beam of length L and width unity, the distributed load is p/unit length, where P is equal to $p \times L$.

This sort of loading we come across in most engineering problems dealing with building or other structural parts.

A beam has to support a load. But the beam itself has to be supported on pillars, on walls of structures, on props, etc. A railway bridge or a river bridge is nothing but a beam resting on more than one support. These supports are the bridge pillars. They can be made of concrete or constructed from steel. The load on such a bridge, which is likened to a beam, consists of its own weight and the load of a moving train or people going over it.

This load on the bridge is ultimately transmitted through the supports, that is, the pillars to the foundation or the river bed.

If such a beam is just allowed to rest on the supports, then we call it a simply supported beam. Fig. 1.14 shows a beam of length AB, supported on two props—one at A and the other at B.

It carries a concentrated load P at C which is the midpoint between A and B. The length

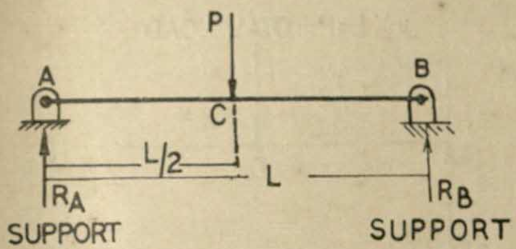


Fig. 1.14

of the beam between the supports (or the distance between the points A and B) is known as the span of the beam. The two supports A and B will have to counteract or balance the nature and character of the load P, and hence on the supports there will be reactions R_A and R_B.

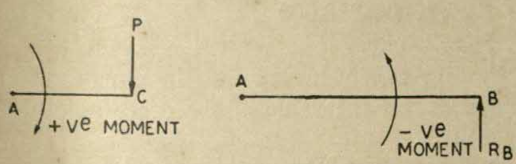


Fig. 1.14.1

Let us assume that these two reactions will be acting upwards as shown by arrowheads in the figure. Let us assume that we know the value of P in kg, the distance AB (i.e. span) and also the distance AC. But we do not know the magnitude of the reactions at the supports R_A and R_B. The problem will be to find out the two unknowns, namely, R_A and R_B. From our knowledge of algebra we know that to solve two unknown quantities, we must be provided with two simultaneous equations. Here also we must have two equations. One equation will be obtained by considering the condition of the forces.

Algebraic sum of all the forces in magnitude and direction will be equal to zero.

The second equation will follow from the condition of moments. Algebraic sum of the moments of all the forces about any point in the plane is equal to zero.

If now AB=L and AC=L/2 then we can write the above two conditions in the form.

$P - R_A - R_B = O$ ....(1.1)

Taking moments about A.

$P \times L/2 - R_B \times L = O$ ....(1.2)

About the point A, P is causing the beam to rotate in the clockwise direction, but R causes the beam to rotate in the anti-clockwise direction.

Let us assume that clockwise moments are denoted as positive moments, while anti-clockwise moments are denoted as negative moments. Similarly, in writing equation (1.1) we have assumed that the forces acting vertically downward are + ve, and those acting vertically upward are — ve.

From the equation (1.2) we get—

$P_B = P/2$

Substituting this value of R_B in equation (1.1) we get—

$R_B = P/2$

Therefore $R_A = R_B = P/2$ is the final solution to such a problem.

If in solving such a problem, the reaction comes as negative, then it will obviously mean that the direction of the reaction will be opposite to the direction shown in the figure. That is to say, instead of acting vertically upwards, it will act vertically downwards.

In this case the load P is a concentrated load. If instead of a concentrated load we have a distributed load, then the best way to solve such a problem will be to make an equivalent diagram in which the effect of distributed load will be shown as a concentrated load. This will be clearly understood by a close look at the Fig. 1.14.2.

After this, the procedure will be exactly as before. A careful study of the few problems solved below will make the idea clear.

There are certain limitations to the solution by triangles talked about so far. For instance, it cannot be applied to cases where the three forces keeping the body in equilibrium are parallel to each other.

Let us now solve a few problems.

PROBLEM 1

A beam having a total length of 1000 mm is supported at the two extreme ends. It carries

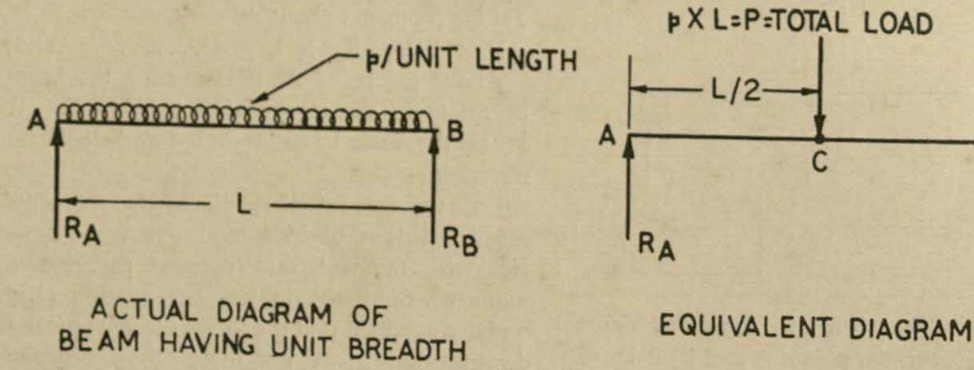


Fig. 1.14.2

three loads of 200, 300 and 100 kg spaced as shown in the sketch. Solve for the reactions at the ends, assuming that the weight of the beam is negligible (Fig. 1.15).

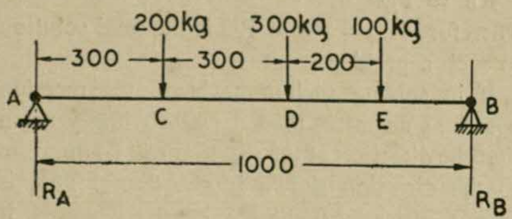


Fig. 1.15

SOLUTION

Solution of this problem is quite easy. In total there are five forces, viz., 200 kg at C, 300 kg at D, 100 kg at E and reactions R_A and R_B.

Condition 1.

Algebraic sum of all the forces equals to zero. Therefore, $200+300+100-R_A-R_B=0$

or $R_A+R_B=600$ ....(i)

Condition 2.

Algebraic sum of the moments of all the forces about any point in the plane equals to zero.

(It is always convenient to take the moments about a point which happens to be the point of application of one unknown quantity).

Let us take the moments of all the forces about the point B. We can write the condition 2 as:

$R_A \times 1000-200\times(1000-300)-300\,(1000-600)-100\times(1000-800)=0$ ....(ii)

$\therefore\ R_A\times 1000-140000-120000-20000=0$

or $R_A\times 1000=280{,}000$

$\therefore\ R_A=280$ kg.

Putting this value of R_A in equation (1) above we get the value of the other unknown quantity R_B.

$R_B=600-R_A=600-280=320$ kg.

Positive values of R_A and R_B only indicate that they act above.

PROBLEM 2

In the same problem as above, there has been imposed an additional distributed load of 0.5 kg per mm length of the beam. Solve the reactions for R_A and R_B. (Fig. 1.16)

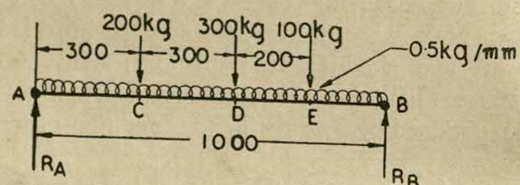
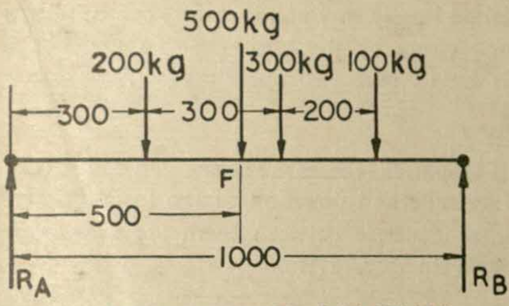


Fig. 1.16

SOLUTION

In solving such a problem what we should do first is to convert the above sketch into an equivalent diagram in which the distributed load will also be shown as a concentrated load. The distributed load of 0.5 kg is equal to a



EQUIVALENT DIAGRAM
FROM Fig. 1.16

concentrated load of $0.5 \times 1000 = 500$ kg. This concentrated equivalent load will always act at the midpoint of the distributed length, i.e., at a point F distant 500 mm ($=1000/2$) from A.

Now the solution of the problem becomes of a routine nature.

$-R_A - R_B + 200 + 500 + 300 + 100 = 0$

$R_A + R_B = 1100$ ....(i)

Taking moments about B.

$R_A \times 1000 - 200\,(1000-300) - 500\,(500) - 300\,(1000-600)$

$-100\,(1000-800) = 0$......(ii)

$R_A \times 1000 = 140{,}000 + 250{,}000 + 120{,}000 + 20{,}000 = 530{,}000$

$R_A = 530$ kg.

Putting the value of R_A (as obtained) in equation .. ..(i)

We get: $R_B = 1100 - 530 = 570$ kg.

Note: The two problems shown here are typical ones. Students are particularly advised to solve as many problems of this nature as possible.

PROBLEM 3

Fig. 1.17 shows two coplanar concurrent forces having magnitude of 150 and 200 kg at an angular spacing of 15°. Find out the moment of the forces about the point 0 lying in the same plane as the forces.

SOLUTION

For the solution of the problem drop from O perpendicular OP on the line AB or its

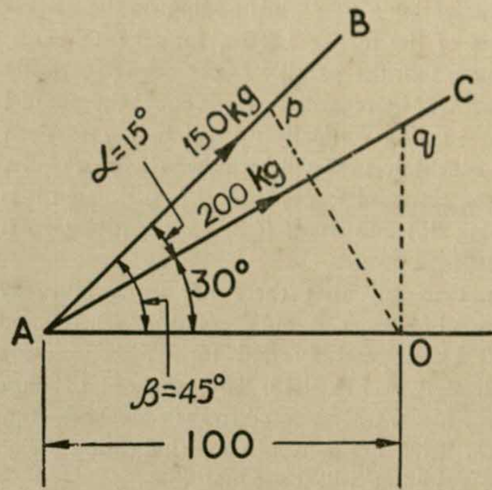


Fig. 1.17

extension and oq on the line AC. The total moment about $O = M_o = 150 \times (OP) + 200 \times (oq)$

$= 150\,(100 \sin 45°) + 200.\,(100 \sin 30)$

$\therefore\ M_o = 150 \times 100 \times 0.707 + 200 \times 1/2$

$= 10605 + 10000$

$= 20605$ kg mm.

Note: The effect of the force AB is to produce a clockwise moment about O. Similarly the effect of AC is also to produce a clockwise moment. And hence the resultant moment will be equal to the summation of the two moments.

1.7 Coplanar Parallel Forces

If forces are coplanar but parallel, that is, lying in the same plane but parallel to each other they can be combined into one resultant force either analytically or by graphical method. The magnitude of the resultant force can be easily measured, since the law states that the resultant of two or more parallel forces is equal to their algebraic sum in magnitude. The difficulty arises in determining the exact point of location of the resultant parallel force as also its direction.

There are cases, met very often, where some of the parallel forces are acting vertically down, while others are acting vertically up. In such a case, we should follow a definite convention

of indicating a sign while adding up the magnitudes of the forces. Let us, for all such cases, assume that the parallel forces acting vertically down will be regarded as + ve and the parallel forces acting vertically up will be — ve. Then the algebraic sum will be either + ve or — ve. If the resultant forces have a positive sign it is acting downwards, if it has a negative sign it must act upwards.

Let us say that there are three mutually parallel forces A, B and C equal to 200, 100 and 250 kg respectively and their directions are indicated in Fig. 1.18. The resultant of these three forces will be equal to their algebraic sum. Now using the convention of indicating a sign the resultant will be equal to—

$$R = +200 - 100 + 250$$
$$= +350 \text{ kg}$$

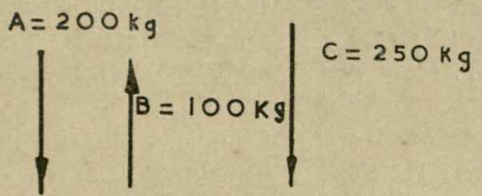


Fig. 1.18

Since the sign is positive, the resultant of these three forces will be acting vertically down. Also we know that it will be parallel to either of A, B or C. But exactly at which point will this resultant parallel force act? We do not know this as yet. A force has three characteristics, namely, (i) magnitude, (ii) direction, and (iii) point of application. In this case we know the magnitude that is equal to 350 kg. Also, we know the direction. It is acting vertically down and running parallel.

To know the third characteristic of the force, viz., its point of application we must be given perpendicular distances between A, B and C. This is, therefore, a prerequisite for finding out the point of application of the resultant parallel force.

The point of application can be determined analytically or by graphical means. The second method is very easy and therefore can be understood easily by the beginners. To understand this let us take two specific cases.

Case I

Two parallel forces are acting vertically down. Magnitude and direction of the forces as well as the distance between them are known (as shown in Fig. 1.19).

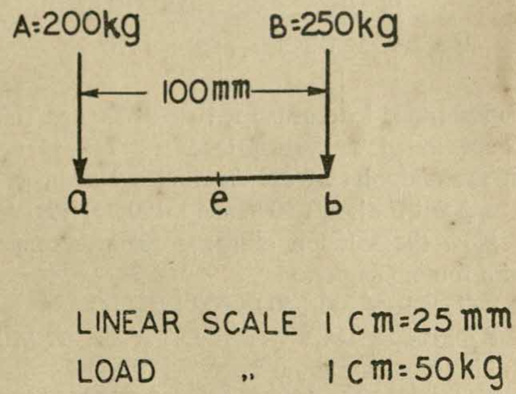


Fig. 1.19

For the graphical construction in Fig. 1.19.1, draw a line *ab* to a scale to denote 100 mm. At *a* draw a perpendicular *ac* to denote the force B to a certain scale. This is to be drawn up. At *b* draw a line 'bd' perpendicularly down to denote the load. A=200 kg to the load scale. Join *cd*, to cut *ab* and *e*. This *e* will be the point of application of the resultant which is equal to (200+250)=450 kg measure 'eb'. Multiply it by the linear scale to get the distance. Analytically, it can be said that the resultant of A and B acts at a point *e* in Fig. 1.19. The distance of *e* from *a* or *b* can be determined by inverse ratio of load, that is,

$$\frac{ae}{eb} = \frac{\text{Load at b}}{\text{Load at a}} = \frac{250}{200}$$

$$\therefore \frac{ae}{eb} = 1.25 \text{ or}$$

$$ae = 1.25 \times (eb)$$

$$ab = ae + eb = 1.25\ eb + eb = 2.25\ eb.$$

but ab=100 mm.

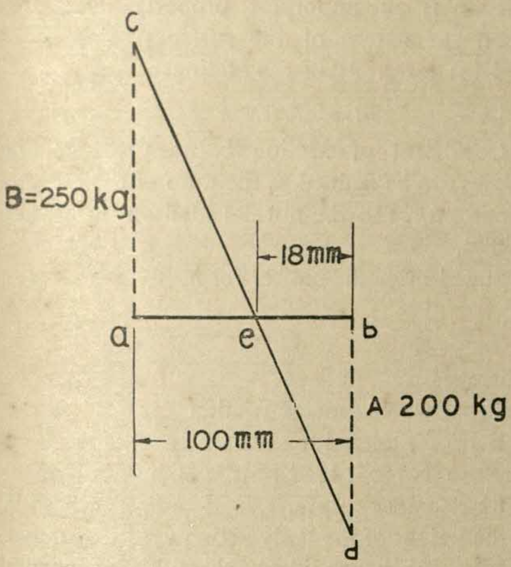


Fig. 1.19.1

$\therefore$ 100=2.25 eb or eb=100/2.25=44.4 mm.

$\therefore$ ae=100—44.4=55.6 mm.

Case II

If the force at *b* is acting in opposite direction then Fig. 1.19.1 should be so changed that B is drawn opposite to the direction *ac*. When Cd is joined and produced, *ab* is also produced. These two lines meet at *e*, as shown in Fig. 1.19.2.

Analytically it can be shown just by convention of signs:

$$\frac{ae}{eb} = \frac{\text{Load at b}}{\text{Load at a}} = \frac{-250}{200} = -1.25$$

ae= —1.25 eb

ae+eb=ab= —1.25 eb + eb= —.25 eb

$$\therefore \text{eb} = -\frac{\text{ab}}{0.25} = -4 \text{ ab}$$

$$= -4 \times 100 = -400$$

$$\text{ae} = -1.25 \times \text{eb} = 500$$

eb = —440, it shows that the point *e* is beyond *b* by a distance of 400 mm.

Case III

When there are three parallel forces (with both signs).

In such a case the point of application can be found out by combination as follows:

(a) Find out the point of application of the resultant of the first two parallel forces.

(b) Then find out the point of application of the final resultant force by applying the law of inverse ratio to the combination of first resultant (resultant of first two forces) and the third force.

In this way we can solve for any combination containing any number of parallel forces.

1.8 Friction and Frictional Devices

In sliding one body over another, we experience a resisting force against the direction in which the body is slided. The phenomenon is called friction and this resisting force is known as frictional resistance or frictional force. Since the body cannot start sliding until it gets over the resisting force, the amount of force that one must apply in order to slide the body should be more than the frictional force. And hence

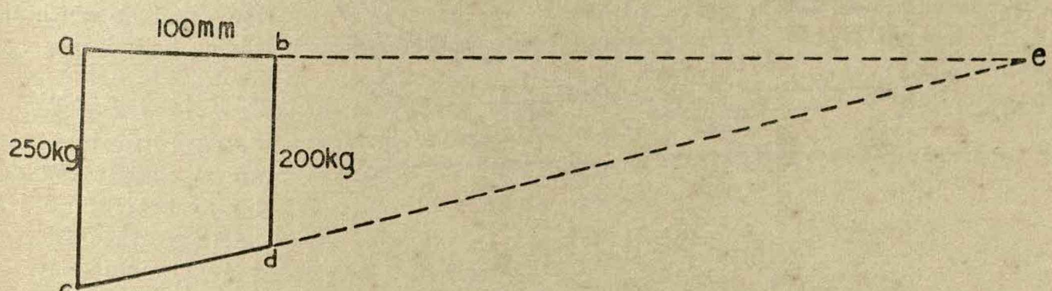


Fig. 1.19.2

the amount of force required will be high if the frictional force is high.

Take the case (Fig. 1.20) of a man pulling a sledge with a force P. Between the ground and the sledge there will be a force of friction. Let F be the frictional force. According to the laws of friction, as P increases, F will also increase. To make the sledge move, the horizontal component of the force P, i.e., P cos α will have to be greater than F. If P cos α is less than F, the sledge cannot move. If we gradually increase P cos α then a stage will come when P cos α will be equal to F. This condition is known as limiting frictional condition. If P cos α is increased slightly the body will move from its position, that is to say, it will start sliding. The friction is called static friction when the body is at rest. The limiting friction can be defined as the maximum value of the static friction when the body is just on the point of sliding. After this condition, any addition to the force P would cause the sledge to move. During the moving condition, the friction force actually falls, depending upon the weight W and the velocity of sliding. This fall in the value of the force of friction, when one body is sliding over another, is called the kinetic (or dynamic) behaviour of the friction force. The friction force, in such a case, is called the kinetic friction force and it depends on the speed of sliding. In solving problems connected with friction we very often refer to a term known as co-efficient of friction. The co-efficient of friction is an important property depending upon the nature of the surfaces being slided and the materials of the sliding bodies.

1.8.1 *Coefficient of Friction*

Coefficient of friction between the sliding bodies can be defined as the ratio of the limiting friction force to the normal load on the sliding bodies.

Stated in mathematical form,

$$f = \frac{F}{N}$$

where

f = Coefficient of friction

F = Frictional resistance to sliding

N = Normal load on the sliding body.

With reference to Fig. 1.20, f = F/W, where W is the weight of the body acting vertically downwards and hence identical with the normal load.

If in the equation f = F/N we substitute F_L for F, where F_L is the limiting force of friction, then

$$f_s = \frac{F_L}{N},$$ where f_s is known as the static coefficient of friction between the sliding materials.

If in equation f = F/N we put F_k for F, where F_k denotes kinetic force of friction or force of friction when one body is actually being slided over the other, then

$$f_k = \frac{F_k}{N},$$

where f_k is known as the kinetic coefficient of friction corresponding to the speed at which the sliding body is moving.

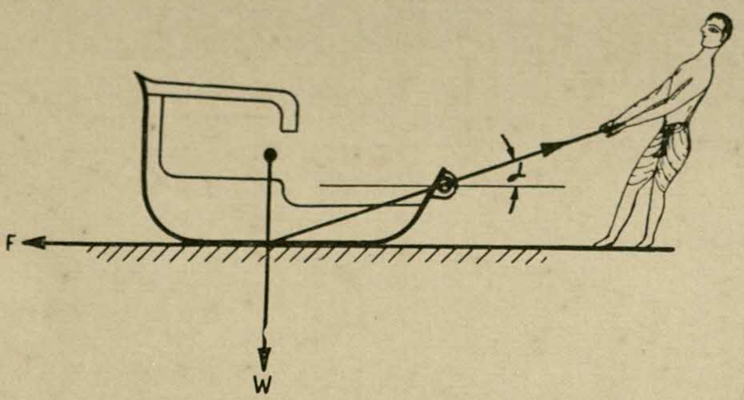


Fig. 1.20

1.8.2 *Laws of Friction*

When two dry bodies are in contact and one body is being slided over another, the friction, brought into play by the act of sliding, obeys certain fundamental

laws. These laws were formulated from various simple experiments carried out by Coulomb, Westinghouse, Morin and others.

These laws can be stated as follows:

FIRST LAW. *Friction between two sliding bodies is not dependent on their area bf contact.*

Bodies A and B are in contact as in Fig. 1.21 (a), but their area of contact is different from that shown in Fig. 1.21 (b). But this difference

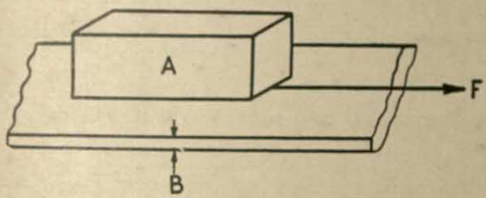


Fig. 1.21 (a)

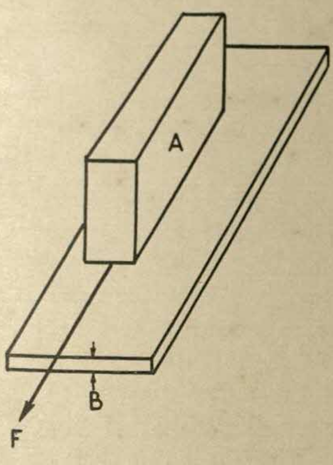


Fig. 1.21 (b)

does not affect the force of friction F which is the same in both the cases.

SECOND LAW. *Friction between two sliding bodies varies directly with the magnitude of load or normal force on the sliding body.*

This law can be illustrated by the two sketches shown in Figs. 1.22 (a) and 1.22 (b).

THIRD LAW. *Ordinary changes of temperature affect the friction force, though very slightly.*

FOURTH LAW. *Friction force decreases as the*

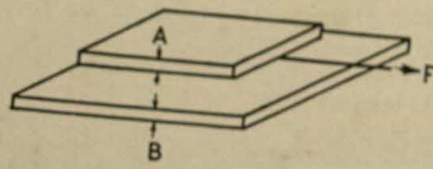


Fig. 1.22 (a)

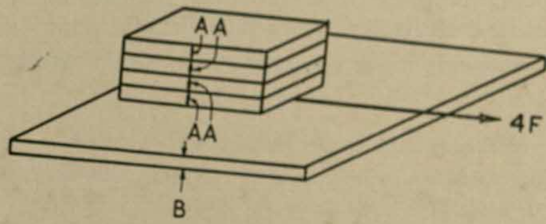


Fig. 1.22 (b)

sliding speed (speed at which one body is slided over another) increases.

FIFTH LAW. *At very slow speeds of sliding, the friction force is nearly independent of the speed.*

SIXTH LAW. *Friction force may be increased by a reversal of motion.*

There are a few more laws of friction, but the six laws stated here are considered to be basic.

1.8.3 *Rolling Friction*

There is, however, another kind of resisting force which is experienced by rolling bodies. This is termed as rolling friction. We know that to push a bicycle on an even road we need some force, even if we want to push it with uniform velocity. This force is needed mainly to overcome the rolling friction between the wheels and the road. Now if we want to push the same cycle on the same road with closed brakes we know that a much larger force would be needed. This is because the wheels are being pushed or slided and not rolled on the road. We see that rolling friction is much lower in value than sliding friction. Still it is important to take this into consideration to find out, for instance, the tractive effort of a vehicle.

A modern automobile needs about 20 to 25 per cent of the total power developed to overcome this friction alone.

1.9 Lubrication

Lubrication is used to reduce the friction between two sliding bodies. If a thin layer of lubricant (the oil used for the purpose of lubrication) is allowed to remain in between the two sliding members, the coefficient of friction will reduce considerably. This reduction in the value of the coefficient of friction depends upon the speed of sliding. As the speed of sliding of one body over another increases, the value of the coefficient comes down. The outer layer of the body surface in sliding contact, if magnified, can be seen to consist of a large number of peaks and valleys. These peaks and valleys are known as surface asperities. As the oil gets into these asperities, it causes an uplifting force tyring to reduce the specific pressure on the sliding surface.

CHAPTER 2

Velocity ratio, mechanical advantage and efficiency; power, I.H.P., B.H.P.; transmission of power by belts and gears; screw jack; wheel and axle; worm and worm wheel; pulley blocks.

2.1 Velocity Ratio, Mechanical Advantage and Efficiency

Man has devised ways and means to lighten his tasks and get over his physical handicap. Our physical strength is limited. Hence the magnitude of weight that a normal man can lift is not unlimited. But there are certain arrangements by which heavier loads can be lifted by applying a smaller force (effort). One of these types of arrangements is known as a lever. Similarly, some methods can be devised that can resist a considerable amount of force.

Any arrangement in which a large amount of work can be performed by using comparatively smaller effort, is called a 'machine' in a broad sense. The basic purpose of a machine is, therefore, either to overcome a resistance or force or to lift a load. And for this we have to put into the machine some effort.

Let us suppose that by the help of a simple machine we can lift a load of W kg through y mm; then the work done by the machine is equal to (W X y) in kg mm. But it is evident that to do this work, we must put into the machine some effort P kg. Let us assume that in lifting W through a distance y, we require P to move through x mm. Then the work done by the effort = (P. x) kg mm.

Work done by the effort is known as 'Input', while work done by the machine (that is, the work that we get out of the machine finally) is known as 'Output'.

Again, we can define input and output in a different way. Input is the work done on the machine and the output is the work done by the machine.

The ratio $\left(\frac{\text{Output}}{\text{Input}}\right)$ is known as efficiency of the arrangement or efficiency of the machine. Thus Efficiency

$$= \frac{\text{Output}}{\text{Input}} = \frac{\text{Work done by the machine}}{\text{Work done on the machine}}$$

$$= \frac{\text{Work done by load}}{\text{Work done by effort}}$$

$$= \frac{(\text{Load}) \times (\text{Distance moved by load})}{(\text{Effort}) \times (\text{Distance moved by the effort})}$$

$$= \frac{W.\,y}{P.\,x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

It should be clearly understood that both load W and effort P take the same time in moving through the distances Y and X respectively.

The ratio $\frac{X}{Y}$ is known as the 'velocity ratio'.

Thus by the 'velocity ratio' we mean the ratio of the distance moved by the effort to the distance moved by the load, during the same period of time.

Velocity Ratio

$$= \frac{\text{Distance moved by effort}}{\text{Distance moved by load}} = \frac{X}{Y} \ldots (2.2)$$

Since in such an arrangement, a smaller effort P can lift comparatively heavier load W,

we get some advantage. This advantage of lifting or moving a comparatively heavier load is known as mechanical advantage.

Mechanical advantage can therefore be defined as the ratio of load to the effort spent.

Mechanical Advantage

$$= \frac{\text{Load}}{\text{Effort}} = \frac{W}{P} \qquad \ldots\ldots\ldots\ldots(2.3)$$

Now we can rewrite the equation 2.1 in the form:

Efficiency

$$= \frac{\text{Mechanical Advantage}}{\text{Velocity Ratio}} \qquad \ldots\ldots(2.4)$$

Efficiency of any machine is always less than 1. But if the entire input energy is converted into output energy then the efficiency becomes equal to 1. This should happen in an ideal machine. But in all practical cases the machine may have bearings, where there is a certain amount of friction. Also, because of windage or other reasons, output energy will be less than input energy. In both these cases efficiency is less than 1. Efficiency which is in fraction or decimal is usually expressed as a percentage by multiplying it by 100. That is to say, an efficiency of 0.9 is expressed very often as 90 per cent.

Let us now discuss a simple problem, where the mechanical arrangement consists of a bell crank lever, as shown in Fig. 2.1.

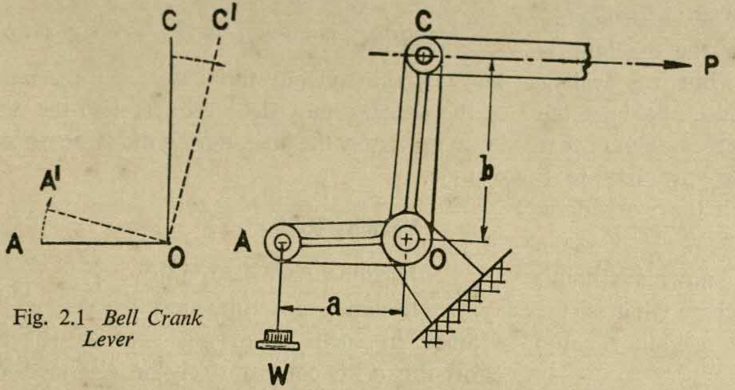


Fig. 2.1 *Bell Crank Lever*

Figure 2.1 shows the bell crank lever AOC hinged at O. At the end C an effort of magnitude P is applied to lift a load W at the end A. The lever has length of the arms AO=a and CO=b. Under the action of the effort P, OC will have the new position OC and AO similarly will move to A'O.

OC=OC'; OA=OA'; and $\angle$ AOC = $\angle$A'OC'
(since this is a fixed angle and cannot change).

Therefore we can say that $\angle$AOA' = $\angle$ COC' = θ say.

The arm lengths AA' = AO $\times$ θ (in radian measure of θ)

CC' = CO $\times$ θ

$\therefore$ AA' = Displacement of W=a θ

CC' = ,, ,, P=b θ.

$$\text{Velocity Ratio} = \frac{\text{Displacement of effort}}{\text{Displacement of load}} = \frac{b\,\theta}{a\,\theta} = \frac{b}{a}$$

$$\text{Efficiency} = \frac{\text{Work done by load}}{\text{Work done by effort}} = \frac{W.\,a}{P.\,b}$$

$$\text{Mechanical Advantage} = \frac{W}{P}.$$

$$\text{Efficiency} = \frac{\text{Work done by load}}{\text{Work done by effort}} = \frac{\text{Mechanical Advantage}}{\text{Velocity Ratio}} = \frac{W/P.}{b/a} = \frac{W.\,a}{P.\,b.}$$

Let us now solve the same problem with some numerical values.

The lever mentioned here has a longer and a shorter arm 600 mm and 200 mm respectively. Manual effort that can be applied at the end of the longer arm does not exceed 20 kg to lift a certain load W at the end of the shorter arm. If the efficiency of the system is 96 per cent, find out the velocity ratio, the mechanical advantage and the magnitude of load W.

SOLUTION

$$\text{Velocity Ratio} = \frac{\text{Displacement of effort}}{\text{Displacement of load}}$$
$$= \frac{\text{Length of longer arm}}{\text{Length of shorter arm}}$$
$$= \frac{b}{a} = \frac{600}{200} = 3$$

Efficiency (expressed in decimal)

$$= \frac{\text{Mechanical Advantage}}{\text{Velocity Ratio}}$$

$\therefore$ Mechanical Advantage
= Velocity Ratio × Efficiency in decimal
$= 3 \times 0.95$
$= 2.85$

$\therefore$ = Load = Effort × Mechanical Advantage
$= 20 \times 2.85 = 57$kg.

Thus by applying an effort of 20 kg at the end C, we can resist a load of 57 kg at the end A.

The same type of analysis can be made for a combination of more than one lever, as shown in Fig. 2.2. In the system shown we have a bell crank lever AOC hinged at O and having the lengths a and b. It is connected to a link CB of length C. The lever BD is connected with CB at B and hinged at E. The lengths BE and ED are equal to d and e respectively. By applying an effort P at the end D we can lift a load W at the end A.

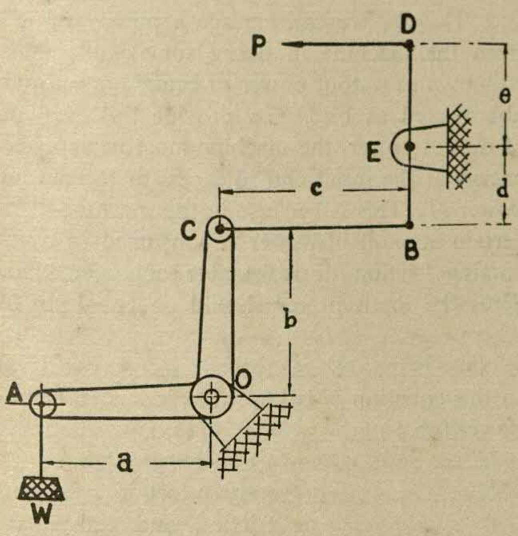


Fig. 2.2

In a case like this, if P moves by an amount x then BC moves by an amount, $\frac{x}{e} \cdot d$.

Since OC is moving by $\frac{x}{e}d$ the arm AO will move by y given by the ratio

$$y = \frac{x}{e} \cdot \frac{d}{b} . a$$

$$\text{Velocity Ratio} = \frac{x}{y} = \frac{x.}{\frac{x}{e} \cdot \frac{d}{b} . a}$$
$$= \frac{b.e}{a\,d}$$

$$\text{Efficiency} = \frac{W./P.}{\frac{b.e}{a.d}}$$

NUMERICAL SOLUTION

If a $= b = 20$ Cm
e $= \quad = 60$ Cm
d $= \quad 30$ Cm
and p $= \quad 20$ kg and W$= 35$ kg,
then Velocity Ratio

$$= \frac{b}{a} \times \frac{e}{d} = \frac{20}{20} \times \frac{60}{30} = 2$$

Mechanical Advantage

$$= \frac{W}{P} = \frac{35}{20} = 1.75$$

Efficiency

$$= \frac{1.75}{2} = 0.875$$

or 87.5%

2.2 Power

If a force P acting on a body moves its point of application through a distance x, then the work done is denoted by the product of P.x. If the force acting on the body fails to displace it, then no work is done. In devaluating the work done, we do not consider the time during which this work is done.

But when we talk about 'Power' we think not only of the magnitude of the work done,

but also the period of time during which the work is done. Thus power can be defined as the rate of doing work. *Power* means the work done per unit time.

Let us now explain this by a simple example of two machines doing the same type of work. Say, we are trying to lift a load of W kg through x meters. If we use machine No. 1, then we find that this lifting is done in t_1 minutes (say), while machine No. 2 can do the same amount of lifting of W in t_2 minutes.

The rate of doing work in Machine 1

$$= \frac{W.X}{t_1} \ \frac{\text{kg m}}{\text{min}}.$$

The rate of doing work in Machine 2

$$= \frac{W.X}{t_2} \ \frac{\text{kg m}}{\text{min}}.$$

Though the work done in both the machines is the same, there is difference in the power developed.

In the foot-pounds system the unit of power is one horsepower. By horsepower we mean the work equivalent to 33000 ft lbs per minute or 550 ft lbs per second. That is to say if a machine can produce in one second 550 foot pounds of work, we say that the machine is producing one horsepower. Similarly, if it does 33000 foot pounds of work per minute, we say it produces one horsepower.

In the metric units, one metric horsepower is equivalent to a work rate of 4500 kilogram meters of work per minute. Power developed or consumed by a machine can also be expressed in kilowatts. One kilowatt is equivalent to a work rate of 6120 kg meters per minute.

Example 1

A machine has got a slider of weight 1000 kg which can move vertically up and down. Find out the power consumed when the slider moves up by 3 meters in 2 minutes. Express the result in 'metric horsepower' as well as kwt unit.

Work done $= 1000 \times 3 = 3000$ kg m.

$$\text{Horsepower} = \frac{\text{Work done in kg m}}{(\text{Period of time in minutes}) \times 4500}$$

$$= \frac{3000}{2 \times 4500}$$

$$= \tfrac{1}{3} \text{ H.P.} = 0.33 \text{ H.P.}$$

$$\text{Power in Kwts} = \frac{3000}{2 \times 6120} = 0.24 \text{ kwts.}$$

Example 2

A train is moving at a speed of 80 kilometers per hour. The total weight of the train is 300 tons, and the total resistance, including the resistance on rails and wind resistance, amounts to 10 kg per ton. Find out the power absorbed in overcoming resistances.

Answer

$$\text{Speed} = \frac{80 \times 1000}{60} = \frac{4000}{3} = 1333 \text{ meters per minute.}$$

$$\text{Total resistance} = 10 \times 300 = 3000 \text{ kg}$$

$$\text{Power absorbed} = \frac{3000 \times 1333}{4500}$$

$$= 889 \text{ hp.}$$

2.3 Indicated Horsepower and Brake Horsepower

Suppose a machine is doing a useful work equivalent to N′ horsepower at the output end. That is, we can extract a power of N′ from the machine in doing some work. This is known as output power or brake horsepower abbreviated as bhp. To provide this amount of output power, the machine must be supplied energy at the input end in excess of the output power N′. This is because in the machine itself certain amount of power is consumed in overcoming friction or resistances of other kind. Thus the input power should be equal to N where

$$N = N' + N'' \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.5)$$

In this equation N is known as indicated horsepower (i.h.p.)

N′ is known as brake horsepower (b.h.p.)

N″ „ „ „ horsepower lost in overcoming friction and resistances. (f.h.p.)

In such a case, the mechanical efficiency of the machine is expressed as the ratio of b.h.p. to i.h.p.

Mechanical Efficiency

$$=\frac{bhp}{ihp}=\frac{N'}{N}=\frac{N'}{N'+N''} \quad \ldots\ldots(2.6)$$

2.4 Wheel and Axle

An axle can be defined as a shaft mounted between two bearings and carrying one or more wheels of a particular diameter connected rigidly to it. The diameter of the wheel must be greater than the diameter of the axle. When the wheel is rotated the axle will also rotate, since they are rigidly connected.

One such wheel and axle is shown in Fig. 2.3. In this figure the axle has got a diameter d and the wheel has a diameter D. A string is fixed at a particular point on the axle and then wound round a few turns. At the extreme free end of this string there is provision for lifting a load W. Similarly another string

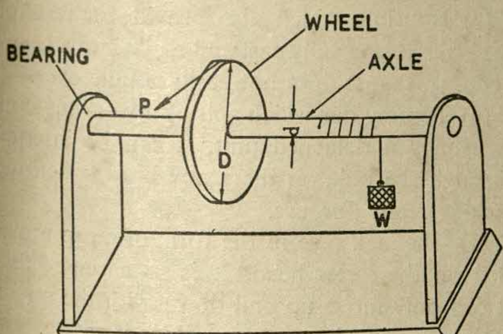


Fig. 2.3 *Wheel and Axle*

is fixed on the wheel and then wound round it. At the free end of this string we can apply an effort P. When the wheel rotates, the axle also rotates freely in the bearing and there is no frictional loss in the bearings. (But in actual case there will also be some amount of friction in the bearings, however insignificant it may be.)

When the wheel and axle make one revolution, then the cord on the axle is wound up by π d and hence the load W is lifted by π d. Similarly, during this period, the wheel moves peripherally by IID.

$$\text{Velocity Ratio}=\frac{\text{Distance moved by the effort P}}{\text{Distance moved by the load W}}$$

$$=\frac{\pi D}{\pi d}=\frac{D}{d}.$$

Mechanical Efficiency

$$=\frac{\text{Work done in lifting the load}}{\text{Work done by the effort}}$$

$$=\frac{W \times \pi d}{P \times \pi D}=\frac{W}{P}\cdot\frac{d}{D} \quad \ldots\ldots(2.7)$$

We can have different types of such arrangements. Instead of the wheel mounted on the axle, we can have a crank mounted on it and the effort in this case can be applied at the end of the crank.

Such an arrangement is known as windlass. It is very often used in raising water from a well or for lifting heavy cargo.

PROBLEM 1

A wheel and axle arrangement is used for raising water from a deep well. The diameter of the wheel is 60 cm while the axle diameter is 12 cm. How much effort should be applied at the wheel to raise a bucket load of water weighing 15 kg, if the mechanical efficiency is assumed to be 80 per cent?

Velocity Ratio

$$=\frac{\pi \times (\text{diameter of wheel})}{\pi \times (\text{diameter of the axle})}=\frac{60}{12}=5.$$

Mechanical Efficiency

$$=\frac{W}{P}\times\frac{1}{\text{Velocity Ratio}}$$

$$\therefore\ 0.80 = \frac{15}{P \times 5};\ P = 3.75 \text{ kg.}$$

$$\therefore\ P = 3.75 \text{ kg.}$$

PROBLEM 2

A windlass used for raising a cargo of 50 kg has the diameter of the axle 10 cm. At the rear

end of the axle is mounted a crank having a length of 18 cm. The effort is applied at the extreme end of the crank length manually. If the effort is equal to 15 kg, find out the mechanical efficiency of the machine.

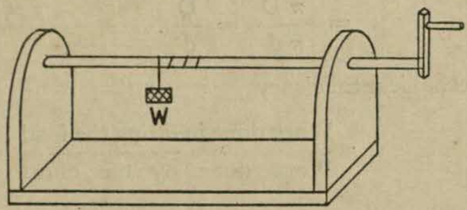


Fig. 2.4

Velocity Ratio

$$= \frac{\text{Peripheral distance moved by crank in one revolution}}{\text{Peripheral distance moved by the axle}}$$

$$= \frac{2\pi \times 18}{\pi \times 10} = 3.6$$

Given, W=50 kg
P=15 kg

and velocity ratio = 3.6

∴ Mechanical Advantage

$$= \frac{W}{P} = \frac{50}{15} = \frac{10}{3} = 3.33$$

Mechanical Efficiency

$$= \frac{\text{Mechanical Advantage}}{\text{Velocity Ratio}} = \frac{3.33}{3.60} \times 100\%$$

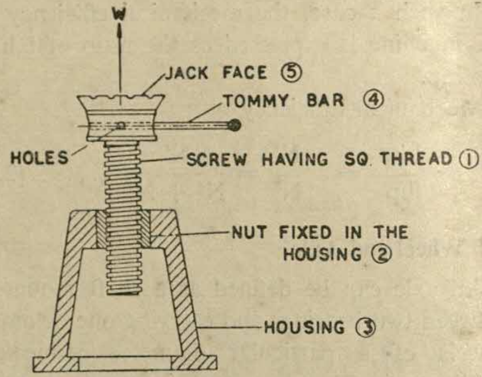
$$= 92\%$$

2.5 Screw Jack

The principle of construction of a screw jack is simple. It usually consists of five essential parts:

(1) The screw, having single start square thread. This screw has a head at the top end. Into this there are holes drilled at right angles as shown.

(2) The nut, through which the screw passes. This nut is fixed in position in the housing. The nut has also the same single start square thread as the screw. The nut can never come out of the housing while the jack is working.



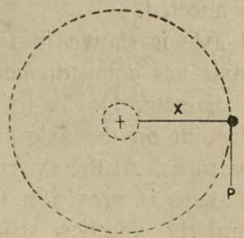


Fig. 2.5 *Screw Jack*

(3) Housing, which also provides a rest for the jack. It is usually cast and made into a heavy body, so that it does not easily topple over.

(4) Tommy bar which acts as a working lever is usually a detached unit. It can be inserted through the hole on the screw head, when the jack is ready for use.

(5) The jack face in the form of a cap provided on the screw head. It is so mounted that it can only move up and down with the screw. But under no circumstances does it rotate.

The main purpose of a screw jack is to lift loads. It is an essential instrument for any workshop. While lifting automobiles or cars we use jack. This type of jack is known as a screw jack since it allows the load to be lifted with the help of the screw movement. In many cases, particularly when we are required to raise comparatively heavier loads, we use jacks operated hydraulically. Such types are known as hydraulic jacks.

We know that screw and nut form a mechanism for transforming rotatory motion to a

reciprocating motion. Suppose a nut is mounted on a screw. If we now rotate the screw in position then the nut will reciprocate along the screw. Conversely, if the position of the nut is fixed, then as we rotate the screw, the screw will either get into the nut or come out of the nut, depending upon the direction of its rotation. This simple basic idea is used in a screw jack. As we rotate the screw with the help of the tommy bar in the clockwise direction, the screw will move vertically down. If the screw is moved in the anti-clockwise direction, then the screw will go up. When the screw goes up, it lifts the load W placed on the jack face. The rotation of the screw is effected by rotating the tommy bar. The tommy bar can be rotated by applying a tangential effort to the end of the bar in the plane paiallel to the base, as shown in the sketch.

Pitch of the screw thread, as we already know, is the spacing between the successive threads and is equal to

$$\frac{1}{\text{Number of threads per unit length}}.$$

In the case of screw thread the lead of the thread is the distance through which any point on the thread profile moves longitudinally by one rotation of the screw. In the case of a single start thread, pitch of the thread is equal to lead of the thread. In the case of threads having n number of start, the lead of the screw $= n \times$ pitch of the thread. When we rotate the tommy bar by applying a tangential effort P then the effort moves by $2\pi x$, in one revolution of the tommy bar, where x is the length of the bar measured from the centre of the screw.

And in one revolution the screw will move up by a distance equal to load. So the load W placed on the jack face will also move up by a distance equal to load. Assuming that the screw here has single start thread, load of the thread= pitch of the screw=p.

∴ Velocity Ratio

$$= \frac{\text{Distance moved by effort P}}{\text{Distance moved by load W}}$$

$$= \frac{2\pi . x}{p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.8)$$

Mechanical Efficiency

$$= \frac{\text{Output}}{\text{Input}} = \frac{\text{Work done in lifting W}}{\text{Work done by effort P}}$$

$$= \frac{W \times p}{2\pi . x . P} = \left(\frac{W}{P}\right)\left(\frac{p}{2\pi x}\right) \quad \ldots\ldots\ldots (2.9)$$

PROBLEM

A screw jack having a capacity of 1 ton has got screw pitch equal to 6 mm. The effort is applied at the end of the tommy bar of length 200 mm. If the mechanical efficiency of the jack is 60 per cent, find out the effort required to be put.

SOLUTION

Given efficiency $= 0.60$ $p = 6$ mm.

$x = 200$ mm. $W = 1000$ kg.

$$0.60 = \frac{1000 \times 6}{2\pi \times 200 \times P}$$

$P = 8$ kg approximately.

2.6 Power Transmission

Rotational speed of one shaft can be transmitted to a neighbouring shaft with the help of certain systems known as 'transmission' or 'drive'.

Transmission systems can be classified into various categories depending upon the arrangement, and accordingly we have:

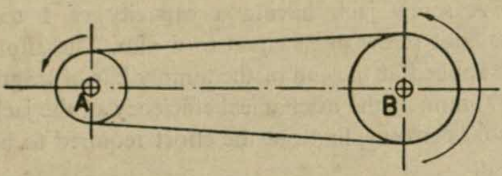
(a) Belt transmission
(b) Friction pairs
(c) Gear transmission
(d) Rope or chain transmission
(e) Worm and Worm wheel transmission, etc.

Of the systems mentioned above, we shall consider the belt, gear and worm transmission.

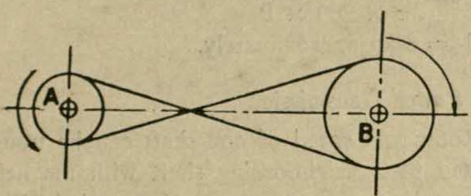
2.6.1 *Belt Transmission*

Let us assume that there are two shafts A and B, parallel to each other and shaft A is running at a certain angular speed N_a revolutions per minute. Shaft B is not rotating. But when we connect shaft B with shaft A by

a tight endless belt, shaft B also starts rotating in the same direction with a certain speed. Here A is known as driver, while B is known as driven. Since the belt requires to be passed round pulleys, we require in such cases two pulleys to be rigidly mounted on shaft A and shaft B respectively. Over these pulleys passes an endless belt made of rubber, leather or other synthetic material.



(a) OPEN BELT OR DIRECT BELT CONNECTION



(b) CROSS-BELT CONNECTION

Fig. 2.6 *Belt Transmission*

Since the pulley, rigidly fixed on shaft, is moving in anti-clockwise direction along with the portion of the belt in contact, the pulley on shaft B will also rotate in the anti-clockwise direction. Let us now assume that there is no relative slip between the pulleys (driver and driven) and the lengths of belt in contact with them. With this assumption we can say that when the pulley A rotates through N_a revolution, any point in the belt will move through $N_a . \pi D_a$, where D_a is the diameter of the pulley A. If now the belt drives the pulley with N_b revolution, then the magnitude of N_b will be obtained from the following:

$$N_b = \frac{N_a \ \pi \ D_a}{\text{Circumference of pulley B}} = \frac{N_a \ \pi \ D_a}{\pi D_b}$$

where D_b is the diameter of the pulley B.

$$\therefore \frac{N_b}{N_a} = \frac{D_a}{D_b} \quad \ldots\ldots\ldots\ldots\ldots (2.10)$$

$\frac{N_b}{N_a}$ is the ratio of the output speed to the input speed and usually denoted by the term 'speed ratio' or 'transmission ratio'. If N_b is less than N_a this ratio is known as 'step-down transmission'. If, on the other hand, N_b is greater than N_a, it goes by the term 'step-up transmission'.

The equation (2.10) shows that the ratio of transmission is equal to the inverse ratio of the diameters of the pulleys.

If in a belt connection we want that the speed of the pulleys should be in opposite direction, then the two pulleys (driver and driven) are connected by a crossed belt, as shown in Fig. 2.6 (b). In the case of a crossed belt connection the length of the belt required is more than that required in the case of open belt connection. The equation (2.10) has been deduced on the assumption that there is no slip in the belt transmission. But in actual practice, slip occurs in almost all cases. To avoid slip we use what is known as 'positive-drive belt'.

It is not necessary for us to deal with the principle of positive drive. The slip can also be eliminated by using a 'chain and sprocket drive'.

Now let us see what happens, when in the transmission there occurs a certain amount of slip.

In such a case, the speed of B will not become N_b but less than N_b. Say, it is N_b'. Then the slip can be expressed by the relationship

$$\frac{N_b - N_b'}{N_b} = S \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.11)$$

where S is the slip expressed in decimal (a 6% slip means that S = 0.06). Slip can therefore be defined as a fractional loss or percentage loss in speed. In expressing the percentage loss in speed, we must multiply S by 100.

Now the equation (2.11) can be written as

$$1 - \frac{N_b'}{N_b} = S \text{ or, } N_b' = N_b \ (1 - S) \ldots (2.12)$$

From equation (2.10.) we know that $N_b = N_a . \frac{D_a}{D_b}$.

Therefore we can express the equation (2.12) in the following form:

$$N_b' = (N_a - \frac{D_a}{D_b}) (1-S) \qquad \ldots\ldots\ldots\ldots (2.13)$$

PROBLEM

A belt drive is used for transmitting speed from the driver shaft to a driven shaft. The driver shaft has a pulley A having a diameter equal to 70 mm and it is running at a constant speed of 1500 r.p.m. (revolutions per minute). The driven shaft has a pulley B of diameter 250 mm. Find out the speed of the driven shaft (a) assuming a slip of 5%, (b) assuming no slip.

SOLUTION

The data available here are:

$D_a = 70$ mm

$D_b = 250$ mm

$N_a = 1500$ r.p.m.

$S = 5\% = 0.05$

We are required to find the speed of driven shaft (that is, speed of driven pulley B) n_b' and n_b.

From equation (2.12) we know that

$n_b' = n_b . (1-S)$.

From equation (2.10) we know that

$\therefore n_b = 1500 \times \frac{70}{250} = 420$ r.p.m.

$\therefore n_b' = 420 (1-S) = 420 (1-0.05) = 399$ r.p.m.

Note: No mention has been made in this problem as to whether the belt is an open one or crossed one. Of course, the ratio of speed does not depend upon this. It is the direction of rotation that depends upon the open or cross connection.

2.6.2 *Gear Drives*

The speed can be transmitted from one shaft to another, placed at a parallel position, with the help of a positive transmission system using spur gears.

It is necessary here to explain the construction of a gear. A gear is nothing but a wheel having certain width. On the periphery of the wheel is cut or formed specially shaped teeth in the form of projections. These teeth have got involute profile on two opposing sides as shown in the sketch. Involute is the curve traced by the end of string unwound from a circular disc. This circular disc represents the base circle.

In Fig. 2.7 (b) the tip circle diameter of the gear is also known as the outside diameter. By circular pitch of the gear teeth we mean the distance between the same points on the flank faces of the successive teeth measured along the pitch circle line. If the pitch circle diameter of a spur gear is denoted by D and the total number of teeth on the gear is Z, then

the circular pitch $= \frac{\pi D}{Z}$.

But the diametral pitch is denoted by $\frac{Z}{D}$.

$\therefore$ Circular pitch $= \frac{\pi}{\text{Diametral pitch}}$.

Inverse of diametral pitch is known as module.

$\therefore$ Module $= \frac{D}{Z}$ and it is expressed in millimeters.

Addendum is the radial length of the tooth lying between pitch circle and tip circle. Similarly, *dedendum* is the radial length of the gear tooth lying between pitch circle and root circle. Dedendum is always greater than addendum by an amount known as clearance. The total radial height of the gear tooth is the summation of addendum and dedendum.

$$\text{Addendum} = \frac{1}{\text{Diametral pitch}}.$$

$$\text{Dedendum} = \frac{1.157}{\text{Diametral pitch}}.$$

$$\text{Total depth} = \frac{2.157}{\text{Diametral pitch}}.$$

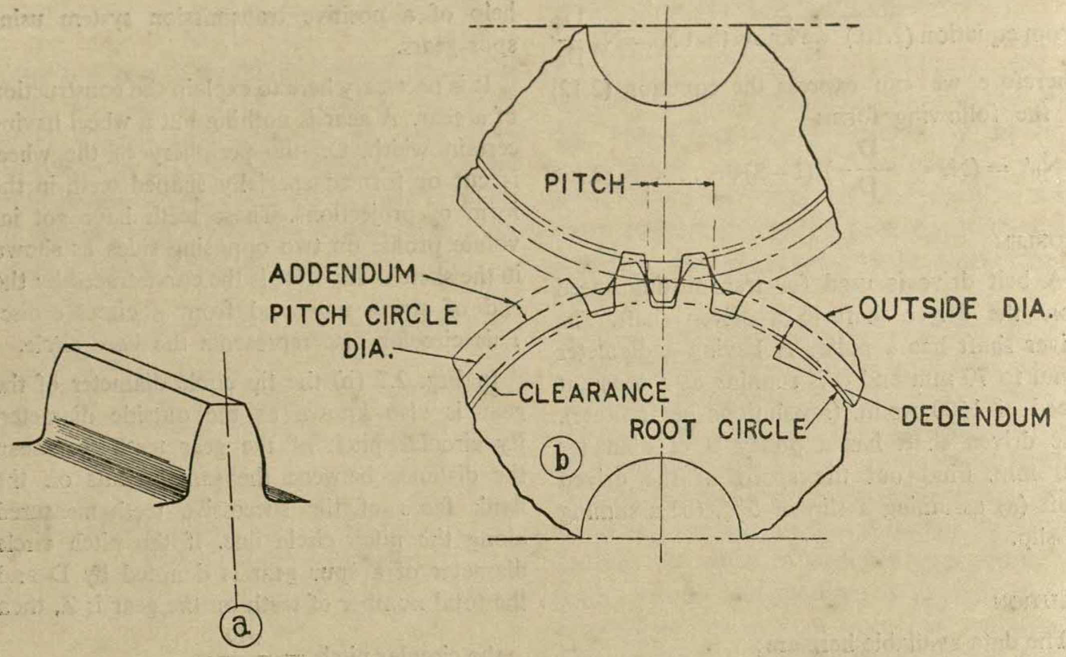


Fig. 2.7 *Gear Transmission*

There are usually more than twenty such teeth in a gear. If these teeth are formed in a manner that the plane of the teeth is perpendicular to the face of the teeth, that is to say, the teeth are straight, then the gear is known as spur gear. If the plane of the teeth is inclined to the face of the gear, then the gear is known as helical gear.

Two such spur gears, used for transmission of speed from one to another, will be meshed in such a way that teeth of one rotating gear will have contact with the teeth of the other, receiving rotatory motion. Usually the teeth contact on the involute profile surface along a line known as pitch line reduces to a point, known as pitch point.

If two gears of different sizes are meshing with each other, then the smaller of the two gears is known as a pinion. The total number of teeth of a pinion cannot be less than 20.

Suppose there are two spur gears G_1 and G_2 meshing each other, transmitting rotation from G_1 to G_2. Also, let us assume that the number of teeth of G_1 and G_2 are Z_1 and Z_2 respectively.

If in a definite interval of time Z number of teeth of each gear pass through the pitch point then,

$$\text{Speed Ratio} = \frac{\text{Revolution of Driver wheel } G_1}{\text{Revolution of Driver wheel } G_2}$$

$$= \frac{\frac{Z}{Z_1}}{\frac{Z}{Z_2}} = \frac{Z_2}{Z_1}$$

$$\therefore \frac{\text{R.P.M. of } G_1}{\text{R.P.M. } G_2} = \frac{Z_2}{Z_1} \frac{\text{Number of teeth in } G_2}{\text{Number of teeth in } G_1} \qquad \ldots.(2.14)$$

By this we can say the speed ratio in a gear transmission equals to the inverse ratio of the gear teeth.

Since in a gear transmission the two gears have positive body contact, the rotation of the wheel G_2 will be in opposite direction to the rotation of G_1.

In case we want that both G_1 and G_2 will have the same direction of rotation, then we

provide an intermediate gear G_3 having any number of teeth Z_3.

$$\text{Then, } \frac{\text{R.P.M. of } G_1}{\text{R.P.M. of } G_3} = \frac{Z_3}{Z_1} \quad \ldots\ldots(2.15)$$

$$\frac{\text{R.P.M. of } G_3}{\text{R.P.M. of } G_2} = \frac{Z_2}{Z_3} \quad \ldots.(2.16)$$

Multiplying the above equations we get,

$$\frac{\text{R.P.M. of } G_1}{\text{R.P.M. of } G_2} = \frac{Z_2}{Z_1}$$ which is the same as equation (2.14). Hence we say that gear speed ratio depends only on the number of teeth of driver and driven and not on the intermediate gear.

2.6.3 *Worm and Worm Wheel Transmission*

Worm and worm wheel transmission is required for transmitting rotatory motion between two shafts which do not intersect. The two shafts in almost all cases are mounted perpendicular to each other. Such arrangement can transmit a maximum speed ratio of 100. Such high speed ratio cannot be obtained by spur gear transmission, since under this condition the size of the gear will be enormous.

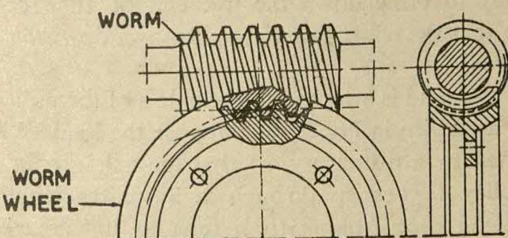


Fig. 2.8

Fig. 2.8 shows the sketch oa worm and worm wheel transmission system. The speed ratio in this case is given by

$$\frac{N_A}{N_B} = \frac{Z_B}{Z_A} \quad \ldots\ldots\ldots\ldots\ldots(2.17)$$

where N_A, N_B are the r.p.m. of the worm and worm wheel respectively

Z_B is the total number of teeth in the worm wheel.

Z_A is the number of start of worm (usually 1 or 2).

Worm gearing can be used for almost any speed ratio. But its efficiency falls as the speed ratio rises. A speed ratio of 1: 50 is ideal for worm-worm wheel transmission. Whenever the reduction required is high of the order of 1: 10 or so, we use 'worm-worm wheel' arrangement.

2.7 Pulley Systems

Pulleys can be very conveniently used for lifting loads. Pulleys are of two characters—fixed pulley, which does not change its position of axis or rotation, and movable pulley—where its axis can be raised or lowered (or moved to another position).

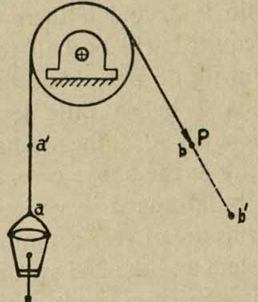


Fig. 2.9 (a)

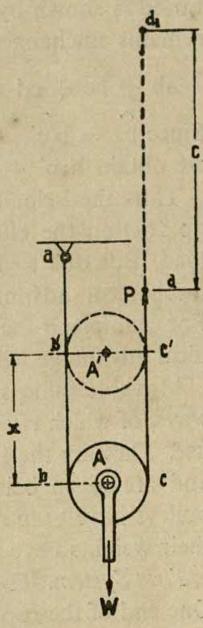


Fig. 2.9 (b)

Fig. 2.9 (a) shows a simple system using a pulley to raise some load W, with a downward pull P of the effort. As the load is lifted from a to a′ the point of application of the effort moves from b to b′, and in this case a a′ = b b′, because the length of the rope remains unchanged. Velocity ratio is one. Under ideal conditions, that is, if there is no friction at the

bearings of the pulley or pulley-shaft, P will be equal to W. But due to unavoidable friction, P will be greater than W, so that in actual case efficiency is less than one. Friction can however be reduced by using ball bearings or by using proper lubricating oil in the bush bearings.

Better mechanical advantage can be obtained by having movable pulleys. A simple case is shown in Fig 2.9 (b). One end of the rope is fixed at a, and the rope passes over the pulley A which is movable. The effort P is applied at the free end d as an upward force. The load is attached to the axle of the movable pulley. Suppose the load is raised from position A to A′, a distance x. At the same time the point of application of effort moves from d to d′, a distance C. The position of pulley A when raised is shown by b′c′. The length of the rope remains unchanged and therefore,

$$ab + \overset{\frown}{bc} + cd = ab' + \overset{\frown}{b'c'} + c'd'.$$

Since $\overset{\frown}{bc} = \overset{\frown}{b'c'}$,

we obtain $b\,b' + c\,c' = 2x$, therefore $2x = c$.

Thus the velocity ratio is 2, and if there is no friction the effort required will be half the load. But due to friction we do not obtain the mechanical advantage as 2 but a little less. For example, if the efficiency is 90%, the mechanical advantage will be 1.8 in the above case.

Movable pulleys can be arranged in various ways, of which two systems are of very common use. They are the 1st system and the 2nd system and are given below. In the cases dealt with, pulleys have been considered to be light so that their weights have been neglected.

First System. The system is shown in Fig. 2.10. One end of the rope is fixed at e to a fixed body, and the rope passes over the pulley 1. The other end is attached to the axle b of another pulley 2. One end of another rope is fixed at f to the fixed body and the rope passes over the pulley 2. The other end of the rope is attached to the axle c of another pulley 3. In this manner the first system can be constructed by adding more and more movable pulleys.

In the figure, 1, 2, 3 are movable pulleys. The last pulley A is fixed in position and is used

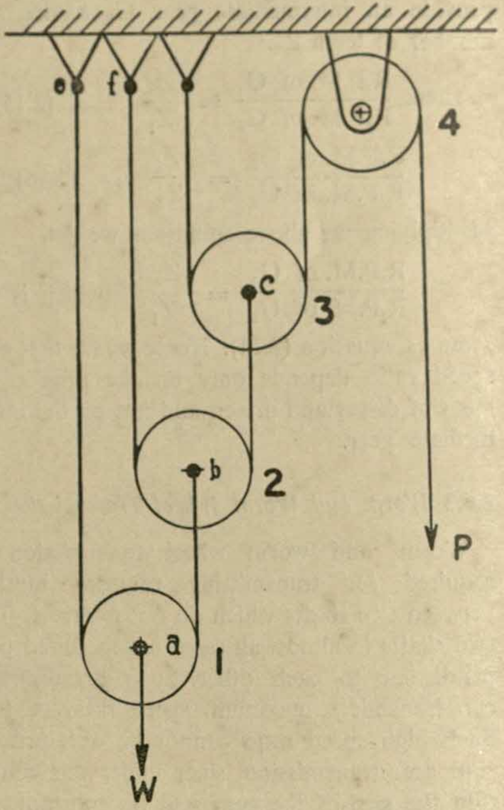


Fig. 2.10

only to bring down the free end of the rope so that the effort can be applied as a downward force.

The load is attached to the axle a of the pulley 1, as shown in Fig. 2.10. Suppose the load W is lifted by a distance y, so that the axle a of the pulley 1 goes up through x. Since the length of the rope from a to b remains unchanged, the axle b of pulley 2 moves up through a distance 2x. Due to the upward movement of the axle b of pulley 2 through 2x the axle c of pulley 3 moves a distance $2.2x = 2^2x$. As the axle c of pulley 3 moves a distance 2^2x, the point of application d of the effort moves through a distance $2x2^2x = 2^3x$.

Thus in the case of Fig. 2.10, the velocity ratio is 2^3. Proceeding in the same manner it can be shown that in the first system the velocity ratio is 2^n, where n is the number of movable pulleys.

Second System. In this system there are two pulley blocks—the upper block and the lower block. The lower block is usually called the bottom block. Each block consists of a number of pulleys. In the second system there is only one rope and the same rope passes over all the pulleys.

In Fig. 2.11, one of the ropes is attached to the upper block. The rope passes over a pulley of the lower block, and then it passes over a pulley of the upper block. Later the rope passes over another pulley of the lower block and in this way it passes over all the lower movable pulleys and the upper pulleys, whose axes of rotation are fixed.

The effort is applied at the free end of the rope and the load is attached to the bottom block. In Fig. 2.11, there are 3 pulleys in the upper block and 3 pulleys in the lower block. Suppose, the load moves up through a distance x. The number of strands of rope between the upper block and the lower block is 6. Then the shortening of the rope lengths between the upper and lower blocks is 6x. Since the total length of the rope is fixed, 6x is equal to the displacement of the free end of the rope.

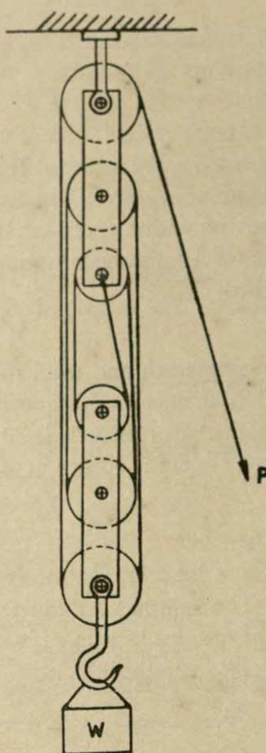


Fig. 2.11

Thus velocity ratio $= \frac{6x}{x} = 6$. Here there are 6 total number of pulleys in the top and the bottom blocks and the velocity ratio is equal to the total number of pulleys used.

With any number of pulleys it can be shown that in the second system the velocity ratio is n, where n is the total number of pulleys used.

In Fig. 2.11, the pulleys are shown with circles of different diameters. In actual practice pulleys of the same size are used and the pulleys of the bottom block are mounted on the same axle. A typical bottom block of simple design is shown in Fig. 2.12.

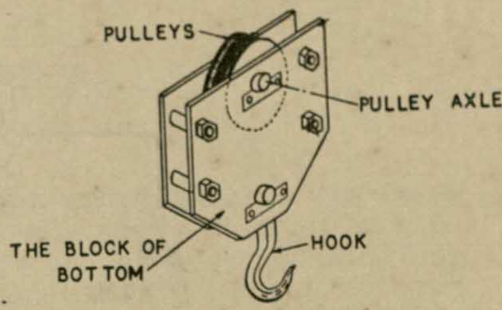


Fig. 2.12

EXAMPLE

A lifting device consists of the first system of pulley. An effort of 20 kg is applied at the free end, which is moved at the rate of 1 m/sec. If there are 4 movable pulleys, calculate the load lifted, assuming an efficiency of 75 per cent. What is the horsepower output of the lifting device and how much horsepower is absorbed in friction?

Velocity Ratio $= 2^4 = 16$.

Mechanical Advantage

$= $ (Velocity Ratio) $\times$ (Efficiency)

$= 0.75 \times 16 = 12.$

$$\frac{\text{Load}}{20} = 12.$$

$\therefore$ Load $= 240$ kg.

Velocity of the load $= 1/16$ m/sec.

Horsepower output

$$= 240 \times \frac{1}{16} \times \frac{1}{75} = 0.\ 2 \text{ H.P.}$$

Horsepower input

$$= 20 \times 1 \times \frac{1}{75}\ 0.267$$

Horsepower absorbed in friction $=$ 0.267, 0.2 $=$ 0.267 H.P.

EXERCISES

1. Define the terms velocity ratio, mechanical advantage and mechanical efficiency.
(a) In a lever type mechanism shown in Fig. (i), find out the magnitude of the effort P for lifting a load of 100 kg. The load P is applied to the longer arm of the lever manually and the mechanical efficiency of the machine is 90 per cent.
(b) What will be the efficiency if the load is changed to 105 kg?
(*Answer*: (a) 55.5 kg. (b) 94.5%)

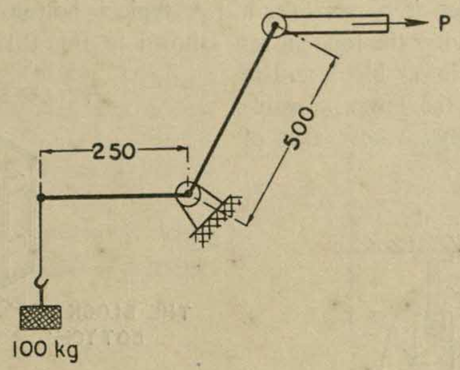


Fig. (i)

2. A motor car having a weight of 3 tons moving with a speed of 100 km per hour is experiencing road and wind resistances. If the total resistances amount to 10 kg per ton of weight of the car, find out the power absorbed.
(*Answer*: 11.1 H.P.)

3. A wheel and axle arrangement is used for raising earth and mud from a pit with the help of a mechanical bucket. The bucket has a maximum capacity of 80 kg. The diameter of the wheel is 100 cm and the diameter of the axle is 30 cm. Find out the magnitude of the effort if the efficiency of the system is 80 per cent. See Fig. 2.3 in this chapter.
(*Answer*: 30 kg)

4. A windlass shown in Fig. 2.4 is used for lifting a load W. At the rear end of the axle is mounted a crank having a length 30 cm. The axle has a diameter equal to 20 cm. The effort P applied at the extreme end of the crank has a magnitude of 20 kg. Find out the magnitude of the load W that can be lifted if the efficiency of the system is maintained at 90 per cent.
(*Answer*: 54 kg)

5. A screw jack used for lifting a weight of 2 tons has got pitch of the screw equal to 6 mm. Effort of 20 kg is applied at the end of the tommy bar, so that its point of application is at a distance of 180 mm. Find out the efficiency of the screw jack.
(*Answer*: 53%)

Describe with a neat sketch the various parts of a screw jack and its principle of working.

6. What are the various mechanical systems commonly available for transmitting power? Describe the method of transmitting power by open and crossed belt.

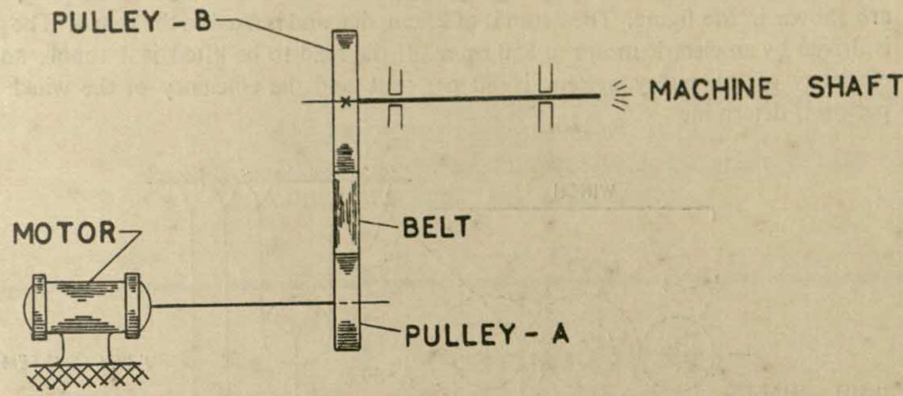


Fig. (ii)

Fig. (ii) shows the method of transmitting rotatory motion to a machine shaft with the help of open belting. The motor is running at a speed of 1440 revolutions per minute (r.p.m.). On the motor shaft there is a driver pulley A rigidly fixed. Pulley B on the other end is rigidly fixed on the machine shaft and receives the motion from the pulley A. If the diameter of the pulley B is 250 mm and on the machine shaft the speed is 400 r.p.m., find out the diameter of the pulley A.

(*Answer*: 69.3 mm)

7. If in the above problem, we assume a slip in the transmission of about 6 per cent, find out the modified speed of the machine shaft.

(*Answer*: 376 r.p.m.)

8. Describe with sketches the principle of transmission of motion by the help of gear trains.
Two shafts A and B are connected by gear trains for transmitting rotatory motion. The shaft A is running at r.p.m. of 900, while on the shaft B we require a speed of 400 r.p.m. If the smaller gear has got 35 teeth, find out the number of teeth on the larger gear. Assuming that the teeth must be of full number, calculate the changed speed of the shaft A.

(*Answer*: 79 teeth)

9. Discuss briefly the various pulley systems used in hoisting machinery.
Make neat sketches to explain the principle of functioning.

10. What is meant by power? Explain the significant difference between I.H.P. and B.H.P.

11. A load of 1000 kg is to be lifted at the rate of 0, 2 m^3sec. using the second system of pulleys. There are 2 pulleys in the bottom block and 3 pulleys in the upper block. Assuming an efficiency of 70 per cent, calculate the rope tension at the effort end and the input H.P.
Make a neat sketch to show the arrangement.

(*Answer*: 286 kg; 3.81 H.P.)

12. A mechanical winch lifts a load with the help of the pulley system shown in Fig. (iii). The rope from the pulley system is wound on the drum of the winch. The winch consists of a compound gear train using 4 gears, of which the teeth numbers Z_1, Z_2, Z_3, Z_4 are shown in the figure. The drum is of 25 cm. dia. and is fixed to the gear 4. The gear 1 is driven by an electric motor at 850 r.p.m. If the load to be lifted is 1 tonne, and the efficiency of the pulley system is 80 per cent and the efficiency of the winch is 75 per cent, determine

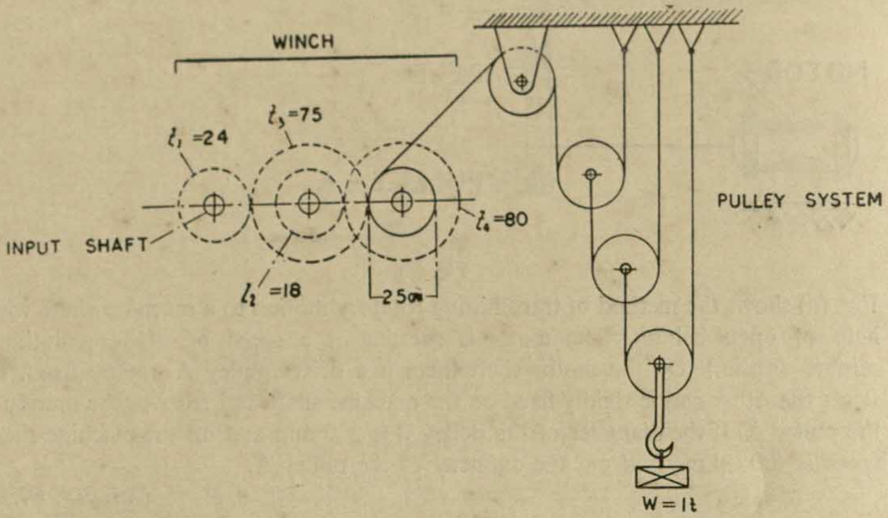


Fig. (iii)

(a) the rate at which the load will be lifted; (b) the horsepower of the motor required to lift the load; and (c) the torque on the motor shaft.

(*Answer*: (a) 6 m/min; (b) 2.22 H.P. and (c) 1875 kgcm).

CHAPTER 3

Temperature and specific heat; total heat, conduction, convection and radiation; properties of gases, fuels and combustion; calorific values of fuels, coal, coke, gas, oil, petrol, etc.

3.1 Introduction

From our basic knowledge of the properties of heat we know that heat and mechanical energy are mutually convertible. Heat energy can be converted into mechanical energy and mechanical energy, likewise, can be converted into heat. The principle of conservation of energy also tells us that the energy lost in one form reappears in another form.

Heat energy can be produced by burning fuel or doing mechanical work. It is a form of thermal energy that can be used for very many purposes. Modern scientists define heat as a mode of motion. A body can be regaded as a conglomeration of minute particles known as molecules held together by cohesion. These particles or molecules are in a state of continuous oscillatory motion. In hotter bodies this motion becomes vigorous. The effect of heating a body is to cause certain changes in the body. Such changes can be mechanical, chemical or electrical

Effects of heat
- (i) Mechanical changes
  - Dimensional change
  - Change in basic properties
- (ii) Chemical changes
  - (i) Change in state
  - (ii) Change in composition
  - (iii) Change in colour
  - (iv) Change in certain basic chemical properties
- (iii) Electrical effect

3.2 Temperature

In a relative sense, temperature can be defined as a degree of hotness or coldness. That is to say, it is the intensity of heat. Temperature, thus, is the quality or extent of hotness, while heat is the 'quantity measure' of hotness. When a body is heated, its temperature rises.

It is this temperature that produces the mechanical, electrical or chemical change in the body. The quantity of heat or total thermal energy of the body depends on three factors, namely, temperature, the weight of the body and the specific heat. Specific heat is again dependent on temperature. Temperature of a body can be expressed as degree Centigrade in C.G.S. unit or as degree Fahrenheit in F.P.S. unit and is measured by an instrument known as thermometer. The freezing and the boiling point temperatures of water under normal pressure in °F unit are 32°F and 212°F respectively. But in °C unit, these values are 0°C and 100°C respectively. Temperature measured in Centigrade unit is denoted by °C, while temperature measured in Fahrenheit unit is indicated by the unit °F.

It is not difficult for us to convert the Centigrade scale into Fahrenheit scale.

$$^{\circ}F = \frac{9}{5} \times {}^{\circ}C + 32$$

$$\text{or } ^{\circ}C = \frac{5}{9} \times ({}^{\circ}F - 32.)$$

Units of heat are usually B.T.U. (British Thermal

Unit) or C.H.U. (Centigrade Heat Unit). By one B.T.U., we mean the total quantity of heat required to raise the temperature of one pound of water through 1°F. By one C.H.U., we mean the total quantity of heat required to raise the temperature of one pound of water through 1°C.

In raising the temperature of 1 gram of water through 1°C, the quantity of heat is called one calorie. 1 C. H.U. = 1.8 B.T.U. = 454 calories.

3.3 Specific Heat

It is quite natural that the amount of heat required to raise one gramme of water through 1°C should be different from that required to raise one gramme of, say, steel, through 1°C. This is because water and steel have different values of specific heat.

Specific heat of any substance can be defined as the ratio of the heat required to raise unit mass of the substance through unit temperature difference to the amount of heat necessary to raise the same mass of water through the same temperature difference.

Specific heat of a substance

$$= \frac{\text{Quantity of heat required to raise the temperature of 1 gm of the substance through 1°C.}}{\text{Quantity of heat required to raise the temperature of 1 gm of water through 1°C.}}$$

Thus the specific heat of water is 1. Similarly, experiments show that different substances have different values of specific heat.

Specific heat of iron	0.11
Specific heat of aluminium	0.21
Specific heat of copper	0.1
Specific heat of ice	0.5
Specific heat of lead	0.03
Specific heat of steel	0.12
Specific heat of brass	0.09
Specific heat of zinc	0.09

With the help of specific heat we can very easily find out the amount of heat to be added to a substance to raise its temperature through a certain temperature difference. Similarly, we can also find out the amount of heat required to be extracted to cool any substance through a certain temperature drop.

Heat required to be added = Specific heat × Weight of the substance × Temperature rise.

Heat required to be extracted = Specific heat × Weight of the substance × Temperature drop.

If the temperature rise or temperature drop is denoted by T, the specific heat of the substance by K and the weight of the substance by W, then

Heat to be added/Heat to be extracted

= KWT.

PROBLEM

From a heated iron rod weighing 2 kilogrammes about 8000 calories of heat is extracted. Find out (i) the drop in temperature in °C, (ii) the final temperature in °C if the initial temperature is 200°C. (Specific heat of iron is 0.11).

(i) $8000 = 0.11 \times 2000 \times T$

$$T = \frac{4.}{0.11} = 36.3°C$$

(ii) $(200 - T) = 36.3°C$

$\therefore$ Final temperature 200—36.3 = 163.7°C.

PROBLEM

In a vessel containing 350 grammes of water at 20°C is placed 50 gm of copper wire having temperature of 200°C. If the specific heat of copper is 0.1, find out the temperature rise of the water.

SOLUTION

20°C 350 gm water		Copper 50 gm 200°C

↘ ↙

Final temperature Water +Copper	= T°C. (higher than 20°C but less than 200°C.)

Let us assume that the final temperature of water and copper = T°C.

Heat lost by copper = Heat gained by water, assuming that no heat is lost to the outside atmosphere.

Heat lost by copper $= 0.1 \times 50 \times (200 - T)$ calories

Heat gained by water $= 1 \times 350\ (T - 20)$ calories

$\therefore\ 0.1 \times 50\ (200 - T) = 350\ (T - 20)$

$200 - T = 70\,T - 1400$

$71\,T = 1600$

$T = 22.5°C.$

Rise in temperature of water $= (22.5 - 20) = 2.5°C.$

Gases have two different values of specific heat. One is known as the specific heat at constant pressure K_p while the other is the specific heat at constant value K_v. For gases the value of specific heat changes with temperature. Thus for calculating the quantity of heat added or extracted, we must know (i) if heat is added at constant pressure or at constant volume, (ii) average temperature (average between initial and final), (iii) value of K_p or K_v corresponding to the average temperature and (iv) the temperature difference through which the gas is raised or brought down.

PROBLEM

Find out the amount of heat to be added to 50 gms of copper to raise its temperature from 20°C to 100°C, if the specific heat of copper is assumed to be 0.1.

SOLUTION

Temperature Difference $= 100 - 20 = 80°C.$
Heat required to be added $= 0.1 \times 50 \times 80 =$ 400 calories.

3.4 Transference of Heat

Heat is usually transferred from one body to another by any one or more of the following phenomena:

(i) Conduction, (ii) Convection and (iii) Radiation.

Let us suppose that there are two identical bodies of the same material A and B at temperatures T_A and T_B respectively and that T_A is greater than T_B. Since we have assumed that the bodies are of identical weights and made of the same material, the total heat contained in A is greater than that in B.

When such bodies are placed in contact then there will be a tendency of A to part with its excess total heat while the body B will try to gain in heat. As a result, the temperature T_A will fall and the temperature T_B will rise. When the transference of heat will be complete, the resulting temperatures of both A and B will be the same and equal to T where T is greater than T_B but less than T_A.

Conduction

Conduction is a process by means of which heat is transmitted in solids. It can be defined as a process by which heat passes from hotter to colder portions of the same body or from a hot body to a colder body in contact.

The rate at which conduction takes place varies from substance to substance. Some substances are known as good conductors, and some are known as bad conductors. This classification is done on the basis of the rate at which conduction takes place.

We should not confuse this with electrical conductors, which are different from thermal conductors. Here by the term 'good conductors', we mean good thermal conductors. Similarly, by 'bad conductors,' we indicate bad thermal conductors.

Convection

Convection is a thermal process by which heat is transferred in liquids or gases. Suppose we are heating water in a kettle. The particles of water lying at the bottom of the kettle in contact with the metallic surface which is directly placed on the fire gets heated first. As these particles receive heat, they rise up to the topmost layer and their space is immediately occupied by the colder particles of water descending from the top layers. Thus a circulation

of heat takes place and a convection current is set up. This circulation gradually causes the entire water to be heated up till it attains a steady state of temperature. Such a process of carrying the heat from one part of the fluid to another by circulation or current is known as convection.

Radiation

The sun heats the earth by radiation. Similarly, heat is transferred from the fireplace to the furnace wall of a furnace by radiation.

If heat passes almost instantaneously from one body to another through space, that is, without any intervening substance, the process is called radiation. It is nearly the speed of light at which the radiant heat is transmitted to the surrounding objects, and hence we call it almost an instantaneous process.

Materials which are transparent to light allow the radiant heat to pass freely through them. A body radiates heat better, if it is darker and rougher.

The rate at which heat is radiated from a perfect radiator to the surroundings is proportional to the fourth power of the absolute temperature of the radiator. The constant of proportionality is known as Stefan's constant.

3.5 Total Heat of Steam

Let us study now the phenomenon of steam generation. When heat is continuously applied to a certain quantity of water, the temperature of water goes on increasing. Ultimately, the temperature attains a certain value when the water starts boiling. This is known as the saturation temperature. Saturation temperature of any substance is dependent on pressure.

If the application of heat is not stopped at this point, then water gradually changes its state from water to steam, even though there is no increase in temperature. Thus this additional heat applied, after water has reached its saturation temperature, is wholly utilized to change the state from water to steam. This additional heat is known as latent heat. But the heat which was applied to raise the temperature of water is known as sensible heat.

Sensible heat, therefore, can be defined as the heat added to unit weight of water to raise its temperature from zero degree centigrade. Similarly, latent heat can be defined as the heat required to produce a change of state without any increase in temperature.

Total heat for unit weight of steam
= Sensible heat + Latent heat.

Sensible heat is always reckoned from 0°C or 32°F and the saturation temperature is dependent on pressure. Latent heat in a similar way varies with saturation temperature.

Sensible heat of 1 lb of water at t°C=t C.H.U.

Sensible heat of 1 lb of water at t°F=(t—32) B.T.U.

Sensible heat of 1 gm of water at t°C=t calories.

Both these values, namely, sensible heat and latent heat are tabulated in steam tables, along with the saturation temperature for various pressures.

3.6 Fuels and Combustion

Fuels contain combustible elements which readily combine with oxygen. The heat produced during the combination is known as the calorific value of the fuel. The chief combustible elements in fuels are carbon, hydrogen and sometimes a small amount of sulphur.

Calorific Value. Calorific value of a fuel is the heat given out by the complete combustion of a unit weight of fuel. In case of gaseous fuels, it is per unit volume of the gas at normal temperature and pressure.

Higher and Lower Calorific Values. When a fuel at ordinary atmospheric temperature is burnt and the products of combustion are cooled to the original temperature of the fuel, the water vapour formed by the combustion of fuel is condensed and the whole of the heat of combustion is recovered. This total heat of combustion is called the '*True or Higher Calorific value*' of the fuel.

When, however, a fuel is burnt in ordinary furnaces, the products of combustion escape at a temperature above that at which the water vapour would condense. The heat obtained during such combustion is called the '*Lower Calorific value*' of the fuel.

The lower calorific value of fuel is taken for working out the results of boiler and engine trials.

Varieties of Fuel

Fuels may be classified as:

(1) Solid fuels—wood, peat, coal, etc.
(2) Liquid fuels—petroleum, shale oil, tar, alcohol.
(3) Gaseous fuels—natural gas, blast furnace gas, coal gas, producer gas.

Only the more important among them which are usually used are described below:

Coal is the product of vegetable matter which has, over the ages, been decomposed and solidified under great pressure. The character of coal depends on the length of time which has been occupied in its production and on the amount of pressure and heat to which it has been subjected in the strata of the earth.

The chief varieties of coal are, (1) Lignite or Brown Coal (2) Bituminous Coal and (3) Anthracite.

Lignite is intermediate in appearance with properties between peat and true coal. It burns with a very long smoky flame and it is generally non-coking. Specific gravity varies from 1.2 to 1.3.

Bituminous coal burns with a shorter flame and it gives off almost no smoke. Specific gravity varies from 1.28 to 1.42.

Anthracite burns without any flame or smoke and with an intense local heat but it requires a strong draught for its combustion. It is hard and brittle. Specific gravity is between 1.35 and 1.70.

The usual contents in coal are carbon, hydrogen, oxygen, nitrogen, sulphur and ash.

There are some artificial solid fuels also like Briquette fuel, wood charcoal, peat charcoal, coke, etc. Of them, 'coke' is mostly used. It is the solid carbonaceous material left after coal has been heated to a high temperature with a limited supply of air, or, in the case of gas coke, with no air at all. The best coke is prepared from bituminous coal. It is hard, brittle and porous, of a dark grey colour and slightly metallic lustre. The composition of good dry coke is

C = 85 to 95%
S = 0.25 to 2%
ash = 4 to 12%

The calorific value of coke varies from 6600 to 7600 C.H.U. per pound.

Liquid Fuel. The liquid fuel almost exclusively used is obtained from the natural mineral oil petroleum. The crude petroleum as it comes from the well usually contains 83 to 87 per cent of carbon and 11 to 14 per cent of H_2 together with small percentages of O_2, N_2 and sulphur. Its specific gravity varies in general from 0.8 to 0.95 and its lower calorific value is about 10,800 C.H.U. Crude petroleum is a mixture of many hydrocarbons having different densities and different boiling points.

When this crude oil is subjected to partial distillation, we get different residues at different temperatures. Lighter constituents evaporate at lower temperatures. *Petrol or Gas oil* comes off at temperatures 70 to 80°C. The different grades of *naphtha* come off at temperatures 80°C to 150°C. *Paraffin oil* or *kerosene* comes off at temperatures 150°C to 300°C.

Gaseous Fuels. Of different gaseous fuels, *producer gas* is mostly used in gas engines, since it is cheap. It is made from waste combustible materials, such as slack or coke. Steam is blown through a thick layer of slack or coke which is slowly burning in the gas producer; the heat of the burning fuel superheats the steam and raises the temperature above its decomposition temperature. This causes the steam to decompose into its two constituents, O_2 and H_2, which pass upward through the thick layer of fuel. Carbon monoxide will be produced; this, with the N_2 from air supply, will pass away with the H_2 and O_2 from the steam. The mixture of combustible gas thus collected will consist of Co, Co_2, H_2,

hydrocarbons, N_2 and O_2. This is washed and passed into the storage tank from which it is drawn for the driving of gas engines.

Combustion. It is the chemical combination which takes place between the constituents of a fuel and oxygen when the fuel burns. Some typical combustion equations are considered below:

(1) $2H_2 + O_2 = 2H_2O$
hydrogen + oxygen = water

(2) $C + O_2 = CO_2$ (Complete combustion)
Carbon + Oxygen = Carbon dioxide.

(3) $2C + O_2 = 2CO$ (Incomplete combustion)
Carbon + Oxygen = Carbon monoxide.
$2CO + O_2 = 2CO_2$

(4) $S + O_2 = SO_2$
Sulphur + Oxygen = Sulphur dioxide.

(5) $C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$
Ethylene + Oxygen = Carbon dioxide + Steam.

The composition of the products of combustion can be volumetrically obtained by an apparatus known as '*Orsat apparatus*'.

CHAPTER 4

Boilers and mountings: definition and functions; classification, types of construction and the principles of working of smoke tube and water tube boilers, boiler mountings, pressure gauge, water gauge, safety valve, fusible plug, steam cock and stop valve.

4.1 Introduction

The industrial revolution of the nineteenth century meant a great advance in technology and engineering. Human labour was gradually replaced by machines. Indeed the progress of civilisation is marked by the growing use of mechanical power in place of human power. The growth of steam power, development of electrical energy and improvements in the age-old methods of transportation are largely responsible for the industrial development of our country. For producing power we require mainly two things:

(i) A source from which energy can be derived and

(ii) A device for converting this energy into effective mechanical work.

In a railway steam engine, used as a means of transport, both of these essential requirements can be seen as a combined unit.

These two essential requisites can always be seen working simultaneously as a combined unit in any power producing plant.

The energy contained in steam can be fruitfully utilized either for driving an engine or for generating electrical or mechanical power or for heating purposes.

4.2 Boiler—Its Definition and Function

Any closed metallic vessel, in which water is boiled by the application of heat and converted into steam is known as a boiler. The heat that is applied can be obtained by burning coal or some other fuel. Fuels can be solid fuels or liquid fuels. When a fuel, coal or wood, is burnt, the process is called combustion. It is a process in which the chemical energy of the fuel is transformed into thermal or heat energy. The heat energy released when a fuel is burnt can be utilized for transforming water into steam. Thus we see that in a boiler energy transformation takes place and the chemical energy of the fuel is converted into heat energy of steam. This energy of the steam can be used for generating electric power, driving a mechanical engine, obtaining any sort of mechanical power and for heating purposes.

The earliest boiler was probably the one which was used by Hero as early as 130 B.C. The boiler used was of a hemispherical shaped closed vessel in which water was boiled for being converted into steam.

Since then, numerous types of boilers have been constructed. For our purpose, we shall classify the various boilers which we find in modern practice on the basis of their principle of working.

4.3 Classification of Boilers

Boilers can be classified into various types, depending upon their principles of construction, design features, method of firing the fuel, arrangement of combustion, etc.

Basically boilers can be classified into two categories: (i) Fire tube boiler and (ii) Water

BOILERS

- FIRE TUBE BOILERS
  - HORIZONTAL
  - VERTICAL
  - EXTERNALLY FIRED
  - INTERNALLY FIRED
- WATER TUBE BOILERS
  - HORIZONTAL
  - VERTICAL
  - EXTERNALLY FIRED
  - INTERNALLY FIRED

tube boiler. In a fire tube boiler the hot gases produced by the combustion of fuel are allowed to pass through a series of tubes known as fire tubes, used for heating the water. But in a water tube boiler the gases are passed around the tubes. The tubes in a water tube boiler contain circulating water which is converted into steam.

Boilers can be regarded as a combination of two distinct and separate parts, namely, (i) furnace, in which the fuels are burnt to release hot gases produced by combustion and (ii) actual boiler, which is usually a closed metallic vessel in the nature of a cylindrical shell containing water and steam. This is commonly known as boiler shell.

Whether fire tube or water tube, a boiler can be said to be horizontal, if the boiler shell is placed horizontally; similarly, if the boiler shell is situated vertically, we call the boiler a vertical boiler.

A fire tube boiler can be either of the two types (i) externally fired or (ii) internally fired. This depends upon the position of the furnace in the construction. If the furnace is contained in the boiler shell itself, then the boiler is called internally fired boiler. But in an externally fired boiler, the furnace portion is separated out and is constructed outside the metallic boiler shell. In the externally fired boilers the furnace is constructed by brick setting with an inner lining of firebrick.

Internally fired boilers are commonly used for locomotive, traction engines, marine power plant, etc., while the externally fired boilers are exclusively used for stationary boilers. By stationary boilers, we mean boilers used for stationary work. The wide application of stationary boilers is in electrical power generating stations, industries requiring steam for various processing work and in stationary plant requiring steam for heating purposes, etc.

Of the various fire tube boilers present in the market, the following are worth mentioning: Cornish boiler, Lancashire boiler, Locomotive boiler, Scotch marine boiler, etc. Water tube boilers commonly found in the market are commercial varieties known as Stirling boiler, Yarrow boiler, Babcock boiler, etc.

Fire tube boiler is also known as 'Smoke tube boiler.' The relative advantages and disadvantages of the fire tube and water tube boilers have been shown in table 4.1 below.

TABLE 4.1

Relative Advantages and Disadvantages

Characteristic Features	*Water tube boiler*	*Smoke tube boiler*
Passage of hot gases	Hot gases pass around a large number of tubes through which water circulates.	Hot gases from the firebox pass through the tubes around which the water is kept.
Heating surface	Heating surface is normally large in relation to the total space.	Heating surface is less than that of water tube boiler, in comparison with the total available space.
Elements of the boiler	Different parts of the boiler can easily be dismantled and thus the boiler can be easily transported.	In the case of smoke tube boilers the transportation is not as easy as in water tube boiler.
Maintenance cost	Normally high.	Lower than the maintenance cost of water tube boilers.
Transference of heat	Heat is transmitted quickly and a uniform temperature can be maintained throughout the different parts.	Rate of heat transmission is less.

4.4 Development of Horizontal Boilers

In the early seventeenth century Florenae Raivault produced a steam boiler of spherical shape, as shown in Fig. 4.1. The spherical shaped boiler was made from copper. In this boiler water is allowed to enter through the inlet pipe A by opening a valve E. After the boiler is filled nearly to the neck of the pipe, the inlet, valve E, is closed. Heat is applied by burning wood D. The outlet pipe B is meant for tapping the steam. Here the source of energy, that is, the heat, is obtained by burning wood in the open but around the boiler C. Thus in this system, much of the heat energy of the hot gases produced by burning wood is lost in the surrounding atmosphere. This boiler is actually known as Raivavlt's Bombshell, since his intention was to show the disruptive force of the generated steam. In the original construction the outlet pipe B was temporarily closed by a tight fitting cork. When the water inside the boiler was converted into steam, the steam pressure blew the cork out to show that the steam could exert a disruptive force.

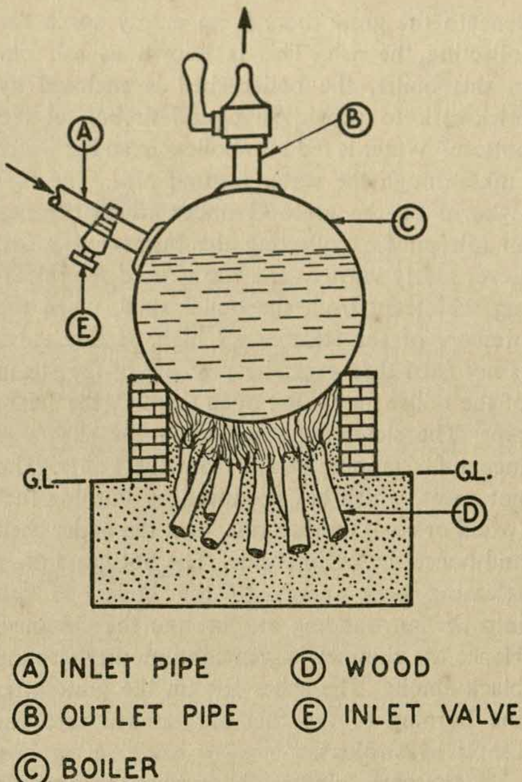


Fig. 4.1 *Raivault Bomb Shell*

Savary's steam boiler of almost identical construction was built in 1702. Here the boiler is either spherical in shape or of a cylindrical shell closed by two dished ends. In Raivault's Bombshell a great amount of hot gases escapes into the air. But in Savary's construction the burning of wood is done in a closed space known as firebox. Thus it is definitely a great improvement on the previous design of Raivault. In this case the firebox contains a platform for burning the fuel. This is known as grate.

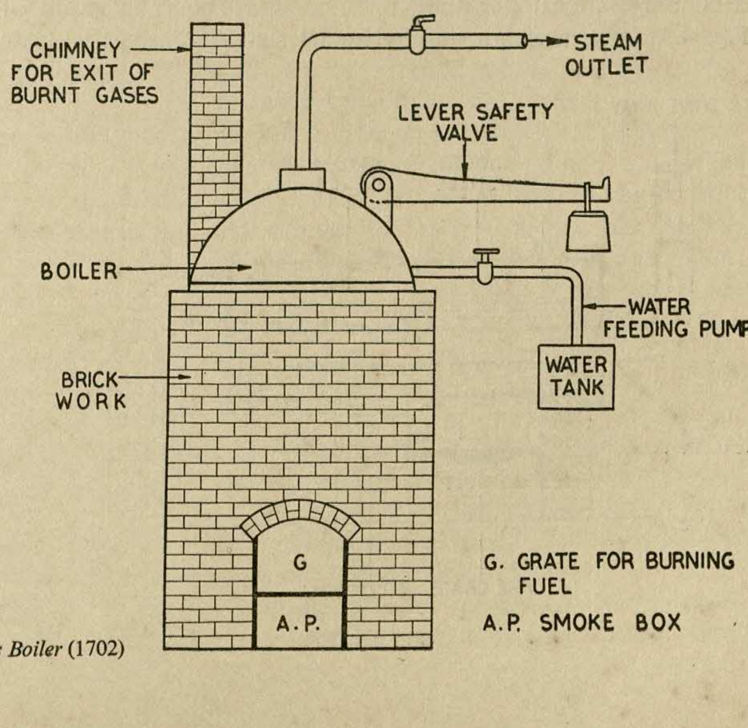


Fig. 4.2 *Savary's Boiler* (1702)

Beneath the grate there is an empty space for collecting the ash. This is known as ash pit. In this boiler, the boiler shell is enclosed by brickwork to provide a closed firebox at the bottom. Water is fed into boilers from the water tank through the water feeding pipe. The fuel is burnt on the grate G under which there is an ash pit for collecting the burnt out ashes. Lever safety valve at the top is used for releasing the steam from the boiler shell, when the pressure of the steam rises high. If this valve is not fixed then excessive pressure of the steam of the boiler may burst open through the steam pipe. The steam pipe shown in the sketch is meant for tapping steam from the boiler. The hot gases, which are produced by burning fuel (wood or coal) on the grate, heat the boiler shell and hence the water inside. The hot gases after releasing heat energy to the boiler go out into the surrounding air through the chimney. Hence the chimney is seen continuously ejecting black smoke. The ashes left on the grate after the burning of the fuel are stroked into the ashpit by strokers.

In the early nineteenth century there was a remarkable progress in the design of stationary boilers using internal flue tubes.

Fig. 4.3 shows a return flue horizontal stationary boiler built in 1800 by an American engineer, Oliver Evans. The important feature of this boiler is the presence of return flue pipe inside the main boiler shell. The boiler is an externally fired one where the fuel is burnt on the fire grate which is supported on brick work. Hot flue gases from the fire grate pass along the passages shown in the figure by arrows and are diverted in their return path through the return flue inside the boiler. After passing through the return flue, these hot gases of combustion escape through the chimney. The boiler shell is filled nearly 3/4th of its volume with water. Transfer of heat between water and the flue gases takes place during the passage of the hot flue gases around the boiler shell as well as through the return flue.

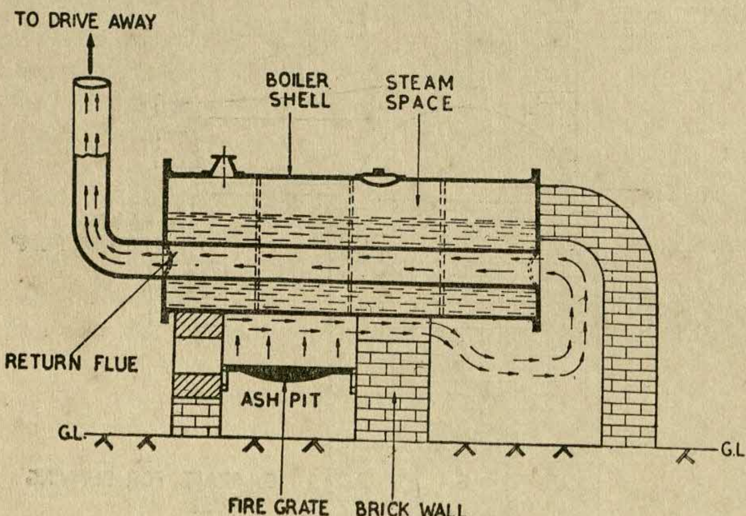


Fig. 4.3

Cornish Boiler

Evans' boiler was regarded as a pioneering invention since all the horizontal and stationary boilers produced later were constructed on the same basic principle. Fig. 4.4 shows the sectional elevation and side-view of a Cornish boiler. Cornish boiler, though very old in origin, is still being used widely as a stationary boiler in industrial plants and factories.

The special features of this boiler are:

(i) This boiler is suitable for raising steam to a pressure 10-12 kg/cm^2.

(ii) There is only one large flue tube running throughout the entire length of the boiler.

(iii) The flue tube is secured inside the boiler shell.

(iv) The boiler shell consists of a number of shells of equal diameter rolled from plates and joined by rivetting.

(v) The grate, constituting the place of burning fuel, is made from

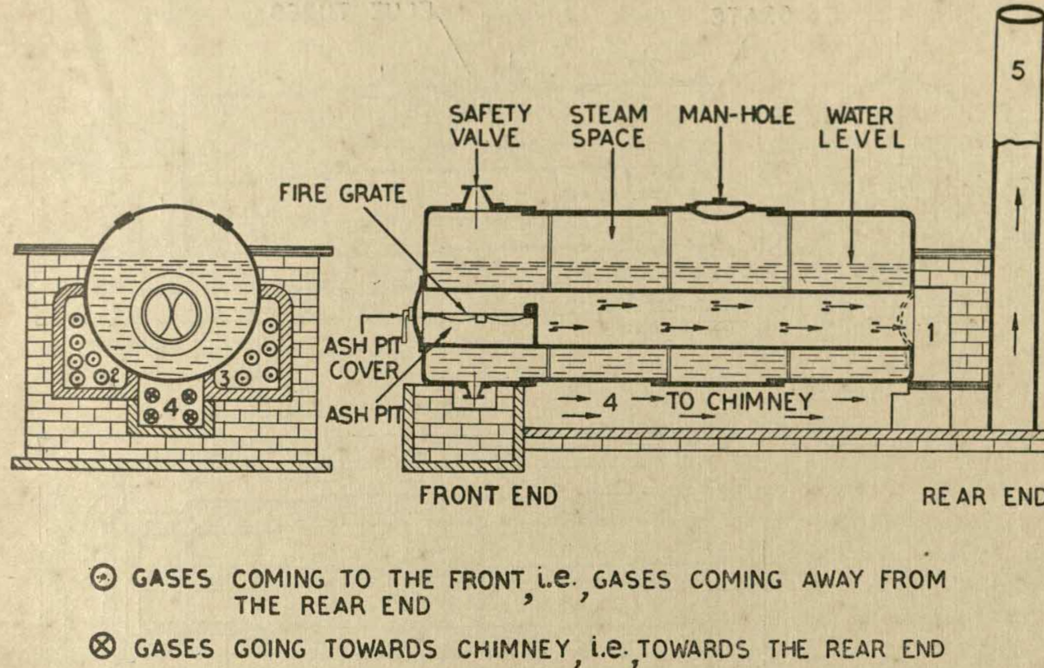


Fig. 4.4 *Cornish Boiler*

bars laid on bearing brackets fixed from the wall of the tube.

(vi) The closed space underneath the fire-place or grate is for the collection of ashes and is known as ash pit. These ashes can be removed periodically by opening the ash pit cover.

(vii) The whole boiler is installed on brick work.

(viii) The chimney is situated at the back, near the rear end of the boiler installation.

Principle of Working

Almost three fourth of the volume of the boiler is filled with water which is required to be converted into steam. The rest of the space is meant for the collection of steam to which the water is raised and is known as steam space. During the firing of coal, sufficient amount of air also enters the area of the grate. By the burning of coal hot gases are produced which are allowed to move along the length of the flue. As these gases pass through the flue, heat is transmitted from the gases to the water through the walls of the flue tube. After reaching the enclosed space marked 1, these hot gases are diverted in their return trip into the side passages marked 2 and 3, running along the length of the boiler. From these side passages the hot gases are again diverted into the bottom space marked 4. The gases in their last journey pass through the passage 4 and go out through the chimney marked 5. Since the gases can transmit heat through the walls of the flue tube and also through the side and bottom walls of the boiler, we get maximum utilization of the heat of the flue gases in raising water to steam. Thus a great economy is effected.

Lancashire Boiler

A typical sketch of the Lancashire boiler is shown in Fig. 4.5. Lancashire boiler is almost similar to a Cornish boiler except that it has a few additional advantages. The extra advantages may be stated as follows:

(i) Pressure to which steam can be raised is slightly higher in a Lancashire boiler,

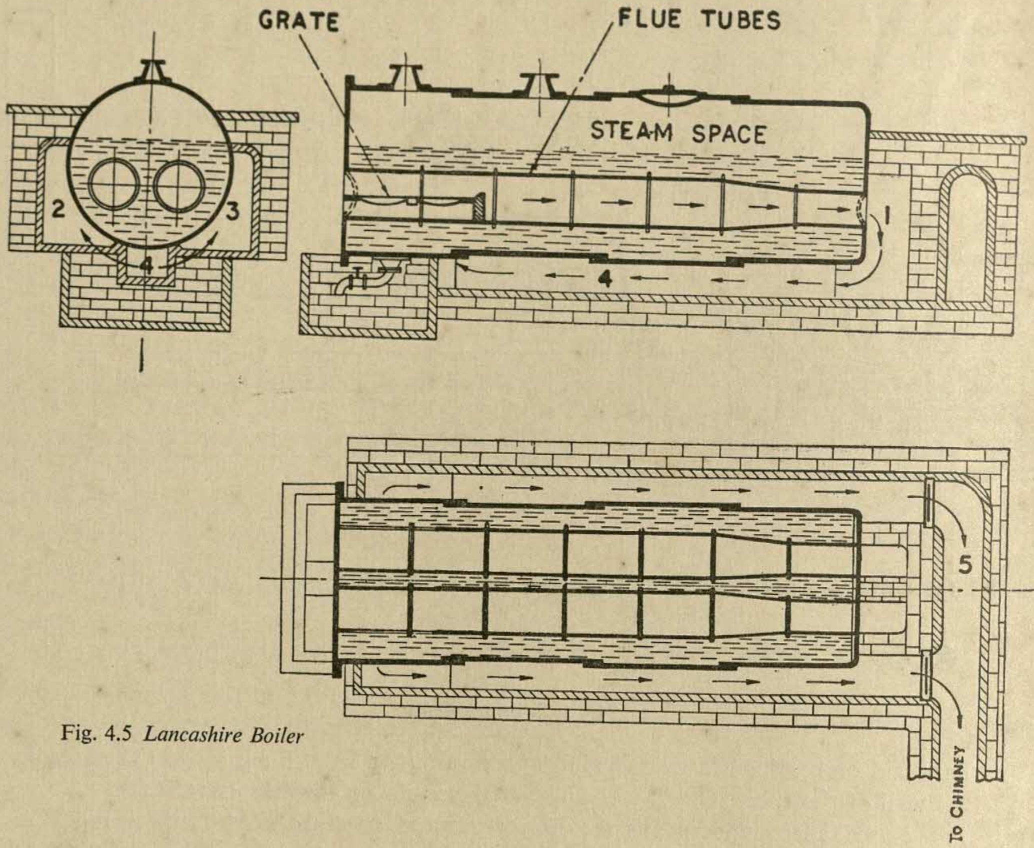


Fig. 4.5 *Lancashire Boiler*

in comparison with a Cornish boiler. Normally we get in a Lancashire boiler steam presssure near about 15 kg/cm^2.

(ii) Capacity of the boiler (by which we mean the total quantity of steam) is higher in this case.

(iii) There are two large flue tubes unlike one in a normal Cornish boiler.

(iv) We get comparatively larger heating area in this boiler.

Principle of Working

The principle of working of a Lancashire boiler is the same as that of a Cornish boiler except that there is a slight change in the passage of the hot flue gases.

The hot gases of combustion pass through the flue tubes from the front end to the rear end of the boiler. When they reach the space 1, these gases are diverted through the bottom channel 4. These gases on reaching the front end of the bottom channel 4 are split into two streams. One of the streams rises to the side channel 2, while the other rises to the side channel 3. These two streams of flue gases are allowed to pass through the channels 2 and 3 alongside the boiler till they reach the space 5 situated at the rear end of the boiler. From the space 5 these gases are allowed to go out through the chimney.

In all these cases of boilers steam is taken out by the steam pipe situated on the top of the boiler shell. There are various other accessories known as mountings which will be dealt with separately.

4.5 Vertical Boilers

We have discussed only some of the stationary horizontal boilers. We shall now see the principle of working of one or two vertical boilers,

that is, boilers with their outer shell standing vertically. The major advantage of the vertical boiler is that it occupies much smaller space in comparison with a horizontal boiler. Such boilers are very widely used in marine installations.

Principle of Working

Fig. 4.6 shows the sketch of a simple vertical boiler. Inside the furnace 2, there is a platform for burning fuel. This platform is known as a grate and is shown as 3. Beneath the grate there is a space for collection of burnt ashes, marked 4 in Fig. 4.6. The coal can be stroked

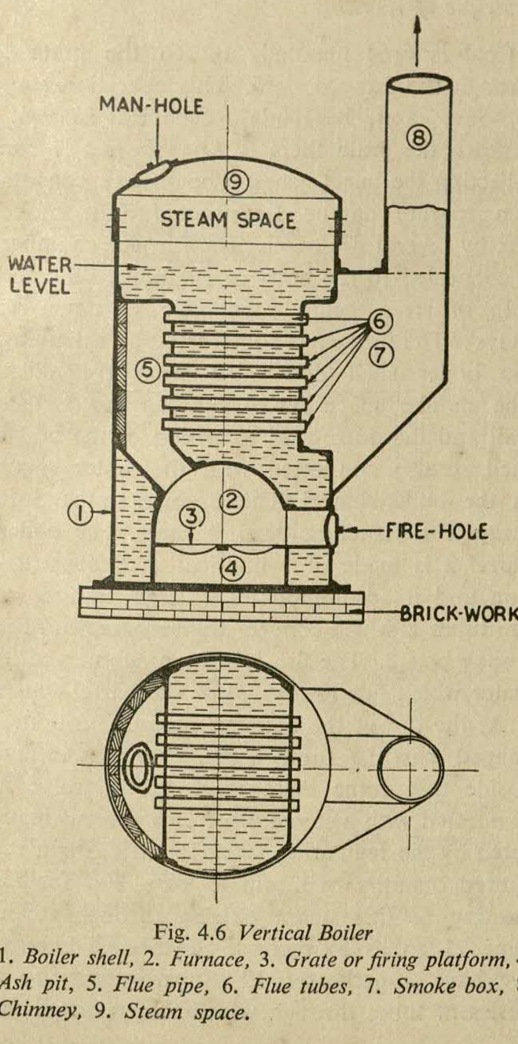


Fig. 4.6 *Vertical Boiler*
1. *Boiler shell,* 2. *Furnace,* 3. *Grate or firing platform,* 4. *Ash pit,* 5. *Flue pipe,* 6. *Flue tubes,* 7. *Smoke box,* 8. *Chimney,* 9. *Steam space.*

inside the furnace either by hand stroker or by mechanical stroker. The hot gases of combustion after the burning of coal pass through the main flue pipe 5. These hot gases pass from the flue pipe 5 to the smoke box 7 through the flue tubes 6. The flue tubes connect the main flue pipe with the smoke box. From the smoke box these gases escape through the chimney 8. The flue pipe and the flue tubes are all immersed in water and the water is filled nearly to 3/4th of the volume of the boiler shell. Hot gases of combustion while passing from the furnace to the smoke box through the flue pipe and flue tubes transfer almost the entire amount of heat to the surrounding water. Water is thereby converted into steam. The steam is collected in the closed space marked 9 over the water level.

It is not necessary that the flue tubes should always be placed horizontally, as shown in Fig. 4.6. In many vertical boilers the flue tubes are also placed vertically.

The specific boiler shown in Fig. 4.6 is also known as multitubular boiler since it contains more than one flue tube for the passage of hot gases of combustion.

In comparison with horizontal smoke tube boilers, vertical smoke tube boiler has the following advantages and disadvantages:

Advantages

(1) Vertical boiler is compact in design and occupies less space.
(2) Vertical boiler is not very expensive.
(3) Vertical boiler is easy to instal and transport.

Disadvantages

(1) Steam raising capacity of a vertical boiler is much lower in comparison with a horizontal boiler.
(2) A vertical boiler very often presents difficulty in cleaning and inspection.

4.6 Water Tube Boilers

As we have already discussed, in a water tube boiler hot gases produced by burning

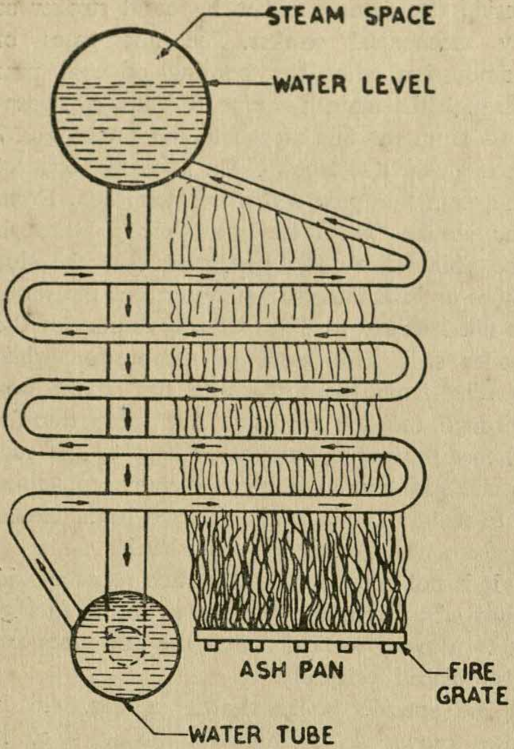


Fig. 4.7 *Water tube Boiler*

fuel in the furnace are allowed to pass around the tube or tubes through which water flows.

Construction and Principle of Working

A simple water tube boiler usually consists of two drums, upper and lower, both containing water. The lower drum is completely filled with water and connected with the upper drum by circulating pipes. The upper drum is partially filled with water. The empty space in the upper drum is meant for the collection of steam. Hot flue gases from the grate rise up around the water tubes and heat the water inside. As a result, a convection current is set up in the circulating water in the direction shown by the arrow. Such a boiler ensures the best utilization of the thermal energy of the fuel in heating the water which continuously circulates.

Water tube boilers can be built for high pressure and large quantity of steam. But such boilers are expensive and present difficulties in servicing.

Schematic diagram of a water tube boiler is shown in Fig. 4.7.

4.7 Locomotive Boiler

In Fig. 4.8 has been shown the sketch of a simple locomotive boiler used for raising steam up to a pressure of 350 $lbs/in.^2$

A locomotive boiler consists of three parts: (i) fire box, (ii) boiler barrel and (iii) smoke box. It can be regarded as an internally fired fire-tube boiler.

Principle of Working

Coal is fired manually on to the grate 4 through the firing door 6. This operation can, in some cases, be made mechanical as well. Beneath the grate there is an ash pan 7 for collecting the burnt ashes. The furnace consists of a separate chamber 1 connected to the smoke box by several fire tubes. The furnace chamber is connected to the body of the boiler with the help of strengthening connections known as 'stays'. The furnace is constructed by extending the boiler shell downward from the sides. The annular space left in between the furnace wall and the downward extension of the boiler shell is also connected with the water space in the boiler barrel. The firebrick arch 5 is meant for deflecting the hot gases. The boiler barrel 2 is made of cylindrical shell construction and it accommodates a large number of fire tubes 8 which connect the furnace with the smoke box 3. The fire tubes are submerged in water which fills nearly 3/4 of the barrel space.

At the top of the boiler is mounted a dome-shaped part 10 for collecting the dry steam. Inside this dome there is a throttle valve A connected with a steam pipe. This valve is regulated by the regulating lever 15, to allow a required quantity of steam to pass. For further heating of this steam passing through steam pipe 11 so as to increase its thermal energy, we have superheater 12. Superheaters are a series of tubes through which the steam passes

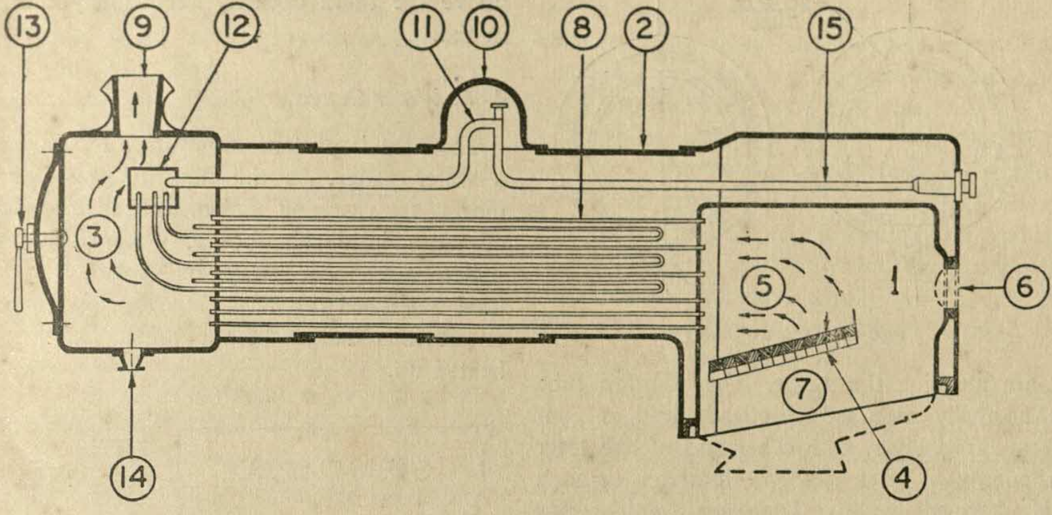


Fig. 4.8 *Longitudinal section of a Locomotive Boiler.* 1. *Furnace,* 2. *Boiler barrel,* 3. *Smoke box,* 4. *Grate,* 5. *Arch,* 6. *Firing,* 7. *Ash pan,* 8. *Fire tubes,* 9. *Chimney,* 10. *Dome,* 11. *Regulator,* 12. *Superheater connection,* 13. *Smoke box door,* 14. *Cleaning outlet,* 15. *Regulator controlling.*

and these tubes are inserted into the fire tubes for further heating. The hot gases from the furnace move through the fire tubes heating the water in the boiler barrel and then pass into the smoke box 3. From the smoke box the hot gases escape through the chimney 9.

The final steam to be used for running the engine is taken out through the steam exit pipe 14.

For cleaning the smoke box from time to time we have a manually operated door 13, as shown in Fig. 4.8.

4.8 Boiler Mountings

Boiler mountings are defined as extra equipment and accessories mounted on a boiler for the purpose of specific measurements, control or uses.

All the diagrams of boilers given earlier in this chapter show only the boilers without any mounting. There are, in fact, a large number of mountings commonly found in an installed boiler. Some of the important mountings are as follows:

(1) Pressure gauge
(2) Water gauge
(3) Safety valve
(4) Fusible plug
(5) Steam cock
(6) Stop valve

Each one of the above mountings serves one specific function, and is essential for the safe running of the boiler.

We shall describe the principle of working of each one of these mountings separately.

4.8.1 *Pressure Gauge*

As the name indicates, it is meant for measuring the steam pressure inside the boiler. To many power plant engineers, it is popularly known as steam gauge. But the 'steam gauge' is not the right name for this device, because it measures only the pressure of the steam inside the boiler, and not its other qualities like dryness, etc. So we will call it a 'Pressure Gauge' or 'Steam Pressure Gauge'. The most commonly used pressure gauge has been shown in Fig. 4.9. The pressure gauge is usually connected with the steam space of the boiler through a syphon or U tube. The syphon contains water or condensed steam and prevents the high temperature

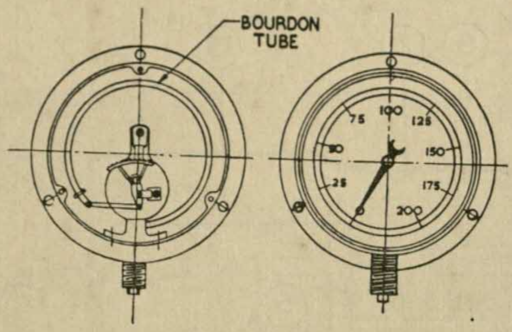


Fig. 4.9 *Pressure Gauge*

steam reaching the gauge. The bourdon tube is normally mounted elliptically and is connected to a lever. The other end of the lever is connected to a gear tooth sector through an intermediate link. The gear tooth sector has teeth meshing with a small pinion. On the same shaft as the pinion is mounted an indicator. This indicator grazes over the dial which is calibrated to show the pressure of the steam. Each boiler is designed to generate steam up to a certain pressure. The scale is made to show $1\frac{1}{2}$ to 2 times the maximum pressure of the boiler. The graduations on the dial beyond the maximum pressure are painted in a different colour. The principle of operation of this type of pressure gauge is quite simple. The pressure of the steam causes the bourdon tube to deform from its elliptical shape to circular shape. Thus the free end of the tube is moved and this movement is amplified by the lever. The movement of the lever causes the gear tooth sector to rotate slightly. This slight rotation of the gear tooth sector means a greater rotation of the pinion which is in contact with it. As the pinion with its shaft rotates, the indicator which is attached to the shaft also rotates. The deformation of the free end of the bourdon tube will be dependent on the steam pressure to which it is connected and hence the rotation or movement of the indicator will also be dependent on the steam pressure.

The dial of the pressure gauge indicates the pressure above atmospheric in kg/cm.^{2} The pressure values up to the rated capacity of the boiler are marked in black while the other values above the rated capacity are usually marked in red.

4.8.2 *Water Gauge*

The next important mounting of a boiler is a water gauge. As the name suggests, it is meant for gauging or measuring the level of water inside the boiler. Water inside the boiler barrel must always be kept at a certain level but when this level falls too low there is an obvious danger of the boiler parts being heated up.

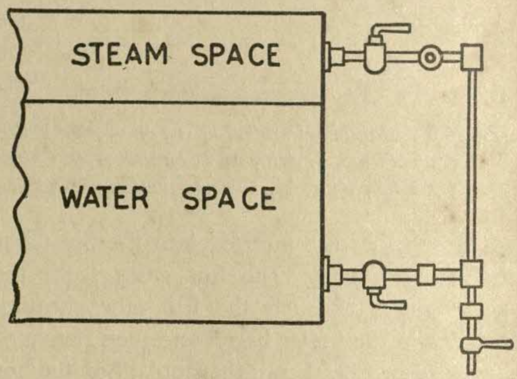


Fig. 4.10 *Water Gauge*

To know the exact level at which the water column stands inside the boiler, we use this water gauge.

4.8.3 *Safety Valve*

Safety valve is the most important of all the accessories that a boiler is fitted with. It is dangerous and almost impossible to use a boiler without a safety valve. The main purpose of the safety valve is to safeguard the boiler, when the pressure of the steam rises higher. As the pressure of the steam generated inside the boiler rises higher than the specified working pressure of the boiler, this valve opens and thereby allows some amount of steam to go out in the air, so that the pressure inside the boiler comes down to the specified limit of the maximum working pressure.

Safety valve therefore serves two objectives:

(i) It saves the boiler from being blown off because of steam pressure rising inside the boiler, and

(ii) it helps the boiler to supply steam at a fairly constant maximum pressure.

A safety valve consists of a circular mushroom shaped valve connected with the steam space of boiler. It is mounted on the top of the steam space of the boiler. By mechanical means this valve is set at a certain specified working pressure. If the steam pressure exceeds this working pressure for which the valve is set, the valve opens out making a definite passage from steam space to the outlet and some steam escapes. Thereby the pressure inside the boiler is brought back to the specified pressure again.

There are three distinct types of safety valves commonly used in a boiler, viz.,

(1) Dead weight type of safety valve,
(2) Spring loaded safety valve, and
(3) Lever type safety valve.

The basic principle of operation in all these types is the same. The only significant difference lies in the different mechanisms provided for the purpose of loading. The valve is so loaded that it can rest slightly against its seat. This compresses the spring and thereby certain quantity of steam escapes from the boiler to the outlet. But the initial position of the valve will be restored as the steam pressure falls below the specified working pressure to which the valve had been previously set.

Fig. 4.11 shows a simplified diagrammatic sketch of a dead weight safety valve. The principle of working can be briefly explained as follows:

The passage between the steam space and the outlet into air is normally blocked by a mushroom valve resting against the valve seat. The valve is known as a mushroom valve, because of its mushroom shape.

The dead weight applied on top of the valve stem engages the valve in its seat. As the pressure in the boiler steam space increases, an increasing amount of force acts on the valve trying to lift it up from its seat. Ultimately if the total force exerted by the steam is greater than the force due to the dead weight W, the valve is lifted up from its seat and the steam escapes from the boiler through the outlet. As soon the pressure inside the steam space falls below the specified pressure to which the valve is set, the valve will again rest against its seat because of the dead weight.

Spring Loaded Safety Valve

The spring loaded safety valve has been shown by a simple sketch in Fig. 4.12. The principle

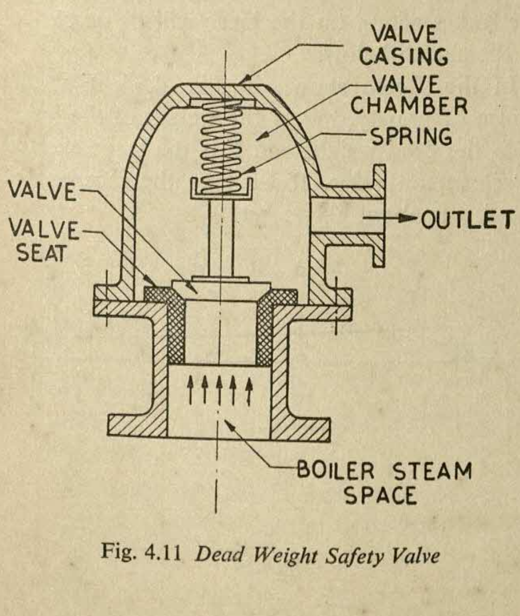


Fig. 4.11 *Dead Weight Safety Valve*

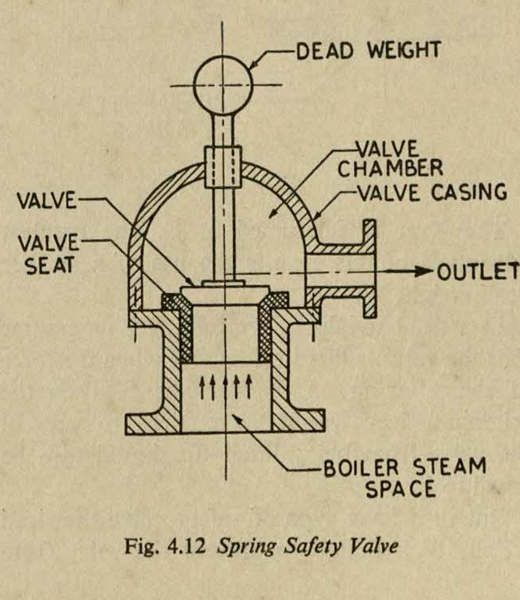


Fig. 4.12 *Spring Safety Valve*

of working in this case is the same as in dead weight type. The only difference in this case is the replacement of dead weight by a helical spring fixed in position. As the pressure inside the steam space starts rising, it applies an increasing force on the valve trying to lift it up. Ultimately when this upward force on the valve is greater than the resisting force applied by the spring, the safety valve is lifted up.

Lever Type Safety Valve

The lever type of safety valve has been shown in Fig. 4.13. In this system the valve is pre-loaded to rest on the valve seat not by the help of a dead weight put directly on top of the valve but by a dead weight placed at the rear end of the lever.

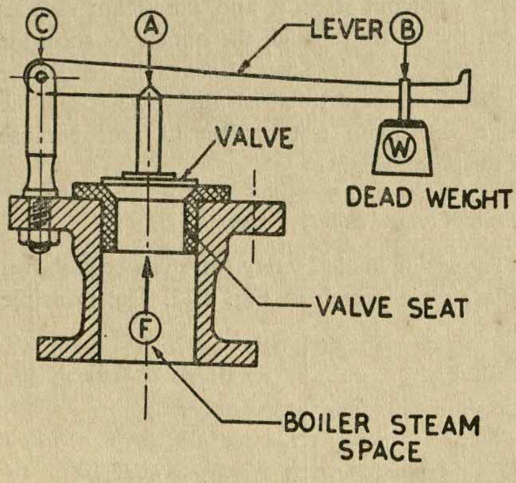


Fig. 4.13 *Lever Safety Valve*

The lever is fulcrumed at C. The greatest advantage of this type is the use of a smaller dead weight W.

In a dead weight safety valve, let us assume that the valve is lifted off its seat when the force of steam acting on the valve is F. Then the minimum dead weight W required to prevent the valve from being lifted up should also be equal to F.

But in a lever type of safety valve the dead weight W, required to prevent the valve from being lifted off its seat when the force of boiler steam is F acting on the valve directed upwards, is given by

$$W = KF \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

where K is a ratio always less than one.

This can be well understood by taking moments of the forces acting on the lever about the fulcrum C. The forces acting on the fulcrum are W at B acting downwards and F at A acting vertically upwards. Therefore, if we take moments of these two forces W and F about the point C, we get

$$W \times BC = F \times AC$$

$$\text{or } W = \frac{AC}{BC} \times F \qquad \ldots\ldots\ldots\ldots\ldots (4.2)$$

AC/BC is the ratio K mentioned in equation (4.1). This being a ratio of a part to the whole is always less than 1. Thus in this type of safety valve, the magnitude of the dead weight required is much less than that in a dead weight type of safety valve.

In this case, of course, we have assumed that the weight of the lever is negligibly small in comparison with W and F. If the lever is not light and its weight is considerable, then the weight of the lever must also be taken into account. The weight of the lever will be directed downwards at the centre of gravity of the lever. Taking into account the weight of the lever, the forces acting on the lever will be as shown in the sketch below.

In the sketch shown in Fig. 4.14, F is the centre of gravity, W^1 is the weight of the lever, W is the dead weight and F is the force exerted by steam on valve. If we take the moment of the forces about C, we get,

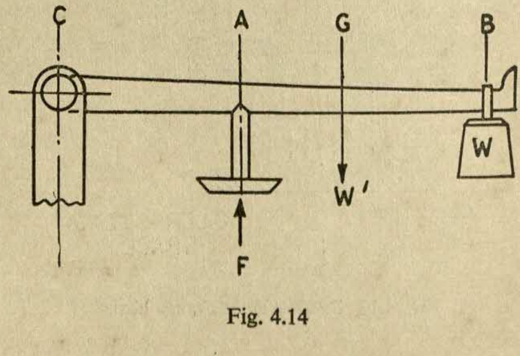


Fig. 4.14

$$F \times AC = W^1 \times (CG) + W\,(BC)$$

$$W = F \times \left(\frac{AC}{BC}\right) - W^1\left(\frac{GC}{BC}\right) \quad \ldots (4.3)$$

The magnitude of W can be further reduced by placing it further away from B towards the free end of the lever.

The lever type of safety valve can be seen on many stationary boilers. But its use is becoming limited now-a-days. A dead weight type of safety valve is mainly used for low steam pressure, i.e., for a low value of F. Otherwise, the weight W becomes too heavy.

The most commonly used safety valve in modern boiler practice is the spring type, since it does not become heavy, nor does it occupy a great space. 'Combination safety valve', using both lever and spring, is also being used in modern boilers.

Besides safety valve, there are stop valves fitted on the outlet pipe of steam connected with the boiler. Most of these stop valves are of non-return type, which means that these valves allow steam only to flow out. These cannot be opened when the steam pressure in the outlet pipe is more than the pressure of steam in the boiler. All these valves can be be regulated manually to control the amount of steam to be flown out of the boiler.

4.8.4 *Fusible Plug*

In all steam boilers of the locomotive type the fire box is fitted with a fusible plug at its crown. The outer chamber surrounding the fire box is also fitted partly with water so that there will be a definite height of water on top of the fire box. The fusible plug is fitted on the top of the fire box, i.e., at the crown (*see* Fig. 4.15). The fusible plug is made of a casting of bronze with a core of practically pure tin, having melting temperature of 200 to 250°C. These fusible plugs can be overheated because of the following two reasons:

(i) level of water falling low, and
(ii) temperature in the furnace rising unduly high.

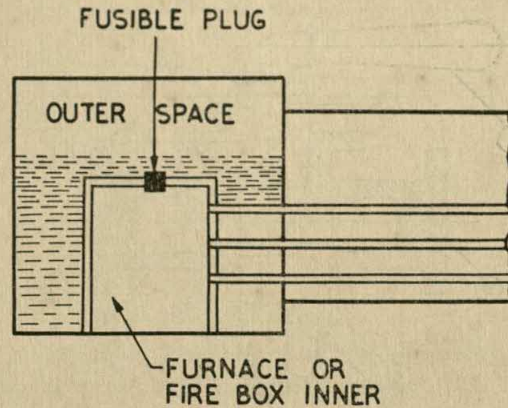


Fig. 4.15 *Position of Fusible Plug*

Overheating causes the fusible plug to melt. When the fusible plug melts, water from top of the fire box falls directly on to the fire place and puts off the fire. Thus the fusible plug definitely acts as a safety device. The typical sketch of a fusible plug has been shown in Fig. 4.16.

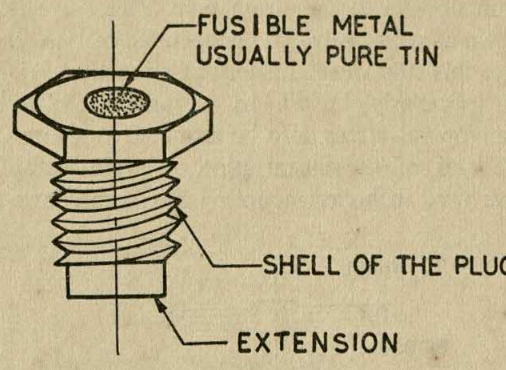


Fig. 4.16

4.8.5 *Steam Cock*

A typical straight way cock with flanged ends, threaded for connection to the main pipe line and fitted with a detachable handle, has been shown in Fig. 4.17. Such cocks are used for regulating the flow of fluid through a pipe. Rotation of the handle through a certain angle (90°) allows the fluid to pass through the opening in the plug brought opposite to that in the shell.

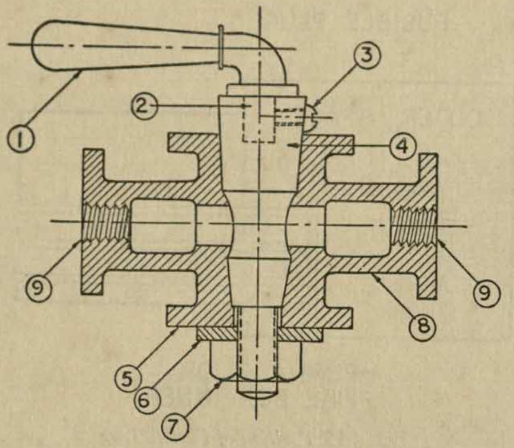


Fig. 4.17 1. *Handle,* 2. *Square shank,* 3. *Screw for fixing handle,* 4. *Plug,* 5. *Bottom flange,* 6. *Washer,* 7. *Nut,* 8. *Shell,* 9. *Pipe thread.*

4.8.6 *Stop Valve*

From the boiler the steam is led to the engine through a pipe known as steam pipe. Usually, at the junction of the boiler and the steam pipe, a valve is mounted to regulate the amount of steam flowing to the steam pipe. This valve is known as steam valve and is operated manually. Since this stop valve is placed at a junction, it is also popularly known as a junction valve. The stop valve may also be mounted at the engine end of the steam pipe. A typical stop valve used in boiler mounting has been shown in Fig. 4.18. The flanged end 1 of the body casting is fixed on the boiler at the topmost point of the steam space by means of bolts. The opening of the valve to the required extent is effected by moving the valve spindle up. At the end of the valve spindle there is a handwheel permanently fixed. As is shown in the figure, the valve spindle has got a considerable length of thread portion which passes through a nut in the body of the bridge. By rotating the hand wheel the valve can be lifted up to any desired height.

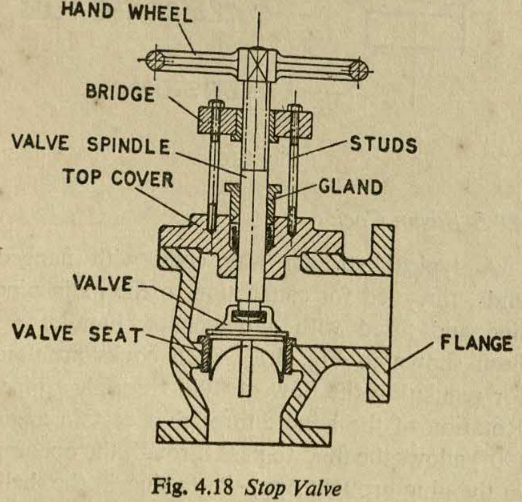


Fig. 4.18 *Stop Valve*

The valve is connected to the valve spindle and is allowed to rest on the valve seat. The valve seat can be changed in case there is too much wearing of its metal. There are various designs of stop valves commonly available in the market. The principle of working of all these types is the same. The nut fixed in the body of the bridge and through which the threaded portion of the valve spindle moves on rotating the handwheel, is usually made of bronze. But the valve spindle is made of high quality hardened steel. The valve seat, similarly, is made of bronze. The main body of the valve casing is often made of brass or bronze for lightness. To prevent escape of steam, gland with packing is normally used.

A stop valve is specified, in practice, by the maximum pressure of the steam that it can handle, viz., a stop valve of pressure 10 kg/cm^2 and so on.

PROBLEM

A lever type safety valve has been designed to operate when the pressure of the steam inside the boiler exceeds 10 kg/cm^2. The effective diameter of the valve on which the steam pressure acts is equal to 5 cm. The length of the lever measured between the fulcrum and the point of suspension of the external weight is 70 cm. The lever is connected to the valve at a point 15 cm from the fulcrum and the valve has its own weight equivalent to 0.5 kg. Find out the external dead weight W to be put at the free end of the lever.

Weight of the lever is 10 kg acting at a point 30 cm from the fulcrum.

SOLUTION

The problem can be represented by the small schematic sketch shown in Fig. 4.19. AF = Effective span of the lever = 70 cm. G is the centre of gravity of the lever, i.e., the point at which the weight of the lever 10 kg acts. B is the point at which two forces are acting: (1) the vertical force due to steam pressure, and (2) the weight of the lever itself which is equal to 0.5 kg. The fulcrum is denoted by F and the distances of the various points from the fulcrum have been mentioned on the sketch.

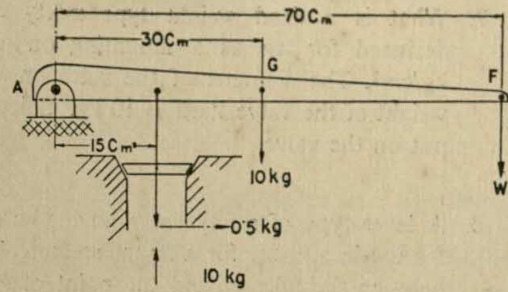


Fig. 4.19

Area of the valve $= \frac{\pi}{4} \times d^2$, where

d = diameter of the valve

$= \frac{\pi}{4} \times 5^2 = 19.6 \text{ cm}^2.$

Steam force P = pressure of steam × area of the valve

$= 10 \times 19.6 = 196$ kg.

Now taking moments of all the forces acting on the lever about fulcrum F we get:

$$W \times 70 + 10 \times 30 + 0.5 \times 15 = P \times 15$$
$$W \times 70 + 10 \times 30 + 0.5 \times 15 = 196 \times 15$$
$$W \times 70 + 300 + 7.5 = 2940$$
$$W = \frac{2940 - 300 - 7.5}{70}$$
$$= \frac{2632.5}{70} = 37.61 \text{ kg.}$$

Therefore, the load to be applied at the free end of the lever to make the valve operate at 10 kg/cm² steam pressure, is equal to 37.61 kg.

EXERCISES

1. Explain the essential difference between a smoke tube boiler and a water tube boiler. Compare the relative merits and demerits of the two types of boilers.
2. Make a neat sketch of a Lancashire boiler without the mountings. Name its various parts and show by arrows the complete flow path of the flue gases from the furnace to the chimney at the exit end.
3. Discuss briefly, with a neat sketch, the principle of the working of a vertical multitubular boiler for marine purposes. What advantages can it have over a horizontal boiler used for land purposes?
4. With a neat and detailed diagrammatic sketch, explain the principle of working of a locomotive boiler. What are the functions of its various parts?
5. What is a pressure gauge? Is it considered to be a safety device or a measuring device or both? With a suitable sketch, explain the principle of working of a steam pressure gauge.
6. What are the various types of safety valves commonly used in the boiler as a mounting? With suitable sketches, describe the principle of operation of the various types of safety valves.

7. What is a dead weight type safety valve? A dead weight safety valve has been designed for use as a mounting on a boiler having steam pressure equal to 15 kg/cm^2. The diameter of the valve on which the steam pressure acts is 4 cm and the weight of the valve itself is 10 kg. Calculate the magnitude of the dead weight to be put on the valve.

(*Answer*: 178.55 kg)

8. A lever type of safety valve having an effective valve diameter equal to 5 cm is meant for use in a boiler for a steam pressure 15 kg/cm^2. The length of the lever measured between the fulcrum and the point of suspension of the external weight is 100 cm. The weight of the lever is 15 kg and acts at a point 45 cm from its fulcrum. The valve is connected to the lever at a distance of 20 cm from the fulcrum. If the weight of the valve and its necessary connections equal 5 kg, calculate the external weight to be suspended at the free end of the lever.

(*Answer*: 51.05 kg)

9. What is meant by fusible plug as used in a boiler? Explain how the fusible plug can work as a safety device.

10. What is a stop valve? Where is the stop valve usually mounted? Explain briefly the principle of its working.

11. A dead weight safety valve used in a boiler has a valve diameter 50 mm. If the working pressure of steam in the boiler is 10 kg/cm^2, what will be the magnitude of the dead weight? By what percentage will this magnitude be changed when the diameter of the valve is increased from 50 mm to 70 mm?

(*Answer*: 196 kg, 385 kg, 96%)

(This problem shows that the magnitude of the dead weight of a dead weight safety valve increases greatly even if we change the diameter of the valve slightly. That is one of the major disadvantages of this type of safety valve).

CHAPTER 5

Steam and its properties; description and operation of steam engines and locomotive engines; various parts of steam engine, such as piston rod, cylinder, valve chest, crosshead, connecting rod, crank and flywheel.

5.1 Introduction

Heat and mechanical work are mutually convertible. Heat can be converted into mechanical work and conversely mechanical work can be converted into heat. The amount of mechanical work converted by one unit of heat is called the mechanical equivalent of heat. The symbol commonly used for this is J. As we know from our earlier studies, unit of heat is either 1 B. Th. U or 1 C.H.U. It has been established by experiments that 1 B.Th.U. can be converted into mechanical work equivalent to 778 ft lbs and 1 C.H.U. correspondingly is equivalent to 1400 ft lbs of work. These are the two values of J in F.P.S. and C.G.S. systems respectively.

Any mechanical device which can convert heat into effective work is known as a heat engine.

Heat engines can be broadly classified under two major heads: (1) Steam engines and (2) Internal combustion engines. In steam engines the working substance is steam. Steam is produced in the boiler, where a certain portion of the total heat generated by burning coal is utilized in transforming water into steam at pressure and temperature above atmosphere. A detailed explanation of the working of the steam boilers has already been given in chapter 4 of this book. The steam from the boiler is allowed to enter into the steam engine. In the steam engine a certain portion of the heat is converted into effective mechanical work. The phenomenon of transformation of heat into mechanical work will be explained in detail while discussing the reciprocating steam engines. The steam after doing useful work in the engine exhausts itself into the atmosphere together with the remaining portion of the total heat.

In internal combustion engines, as the name signifies, the combustion of the fuel takes place inside the engine itself, where the heat is transformed into mechanical work. This is, in fact, the essential difference between steam engines and internal combustion engines.

The present chapter deals with the functional working and the constructional details of steam engines with particular reference to reciprocating engines.

5.2 Reciprocating Steam Engines and Their Classification

Reciprocating steam engine is a variety of the steam engine, where the steam pressure acting on the piston inside the engine cylinder causes the piston to have a reciprocating movement. This reciprocating motion of the piston is converted into rotary motion with the help of a crank-connecting rod mechanism. The reciprocating steam engines commonly found in practice can be conveniently classified as under:

Before explaining the five groups mentioned overleaf, the principle of working of the

RECIPROCATING STEAM ENGINES

Group—I	Group—II	Group—III	Group—IV	Group—V
(Depending upon the direction of action of steam pressure)	(Depending upon location of the cylinder)	(Depending upon the speed of crankshaft)	(Depending upon stages of expansion of steam)	(Depending upon the exhaust pressure above or below atmosphere
(i) Single acting	(i) Horizontal	(i) Slow speed	(i) Simple	(i) Non-condensing
(ii) Double acting	(ii) Vertical	(ii) Medium speed	(ii) Compound	(ii) Condensing
		(iii) High speed		

simplest type of reciprocating engine may be stated. Fig. 5.1 shows the sketch of a reciprocating steam engine.

Inside the engine cylinder (1), there is a piston (4) which reciprocates under the action of the steam pressure. The piston is fitted with one or more (usually more) piston rings (6). The piston is mounted at the front end of the piston rod (5). The trail end of the piston rod enters into the part (12) known as crosshead. The crosshead slides on guides (13) depending upon the movement of the piston.

The guides are used for maintaining directionally precision movement. With the crosshead is connected the connecting rod (14). The end of the connecting rod which fits into the crosshead is known as the small end while the other end, which is connected to the crank (15) by crankpin (16), is known as the big end. The connecting rod is fitted with the crosshead with the help of a pin. This pin allows the small end to rotate on the pin easily. In the figure, (11) denotes the valve chest or steam chest or valve chamber. It is meant for accommodating D-slide valve (9). The slide valve (9) is known as D-slide valve because it is shaped like D. This valve is fixed on the valve spindle (17) which is operated by lever mechanism, to alternately connect the right hand and left hand steam ports (7) with the exhaust port (8).

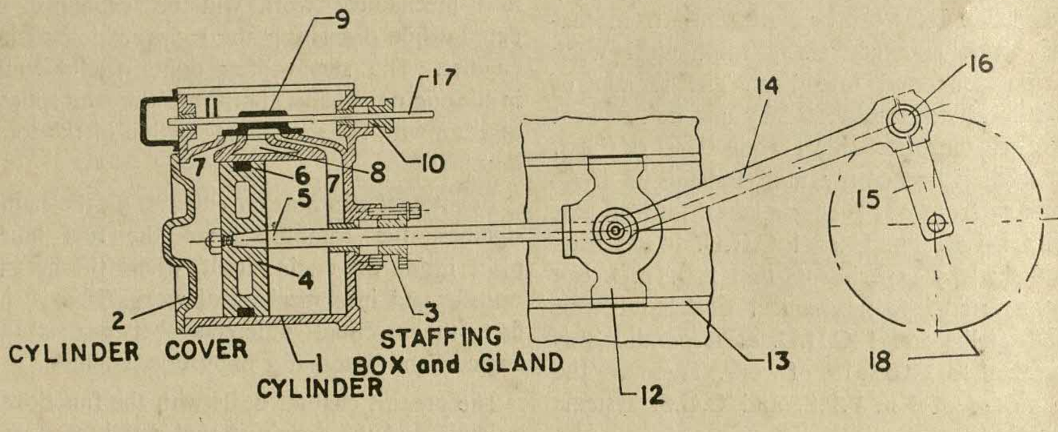


Fig. 5.1

The hole in the cylinder face, through which the piston rod passes, is made steam tight (so that no steam can leak through the peripheral gap between the piston rod and the hole). This is done by fitting a stuffing box with gland (3) using packing material. Similar type of gland packing (10) is used to avoid the leakage of steam from the steam chest to the outside through the peripheral gap between the valve spindle and the hole in the face cover of the steam chest.

The openings (7) through which steam can enter the cylinder from the steam chest are known as steam ports. Two steam ports have been shown in the sketch, one on the left hand side of the cylinder while the other is connected to the cylinder at the right hand side. The opening through which the steam after doing its work in the cylinder can escape into the atmosphere is known as exhaust port denoted by (8). The steam passages are made as short as possible. The exhaust port is connected to atmosphere in non-condensing engines. But in condensing engines, this port is connected to the condensers.

The essential principle of working of such a reciprocating engine is not very difficult to follow. The steam chest receives steam from the boiler straight by the help of steam pipe.

As the slide valve moves to the right, it gradually uncovers the steam port (7) on the left hand side of the cylinder. The steam enters the cylinder through this port from the steam chest and acts on the area of the piston. The pressure of the steam causes the piston to move. As the piston moves, any low pressure steam (from previous operation) occupying the space on the right side of the piston goes out through the right hand steam port (7) and then through the exhaust port (8) to the atmosphere. When the valve moves from right to left, steam gets into the cylinder through the right side port (7) and pushes the piston in the opposite direction. And in this position the left hand side port (7) is connected to the exhaust. Thus we get the reciprocating movement of the piston inside the cylinder.

As the steam inside the cylinder expands because of the increase in volume caused by piston movement, its pressure falls. The steam which goes out of the cylinder, therefore, has a pressure much lower than that entering into the cylinder. But normally the pressure of the exhaust steam should be a little above atmosphere, otherwise we will not be able to send it out to atmosphere.

As the piston reciprocates inside the cylinder, the crosshead connected to its other end slides to and fro inside the guides. These guides are sometimes known as slide bars. As the crosshead moves to and fro, the crank pin (16) moves along the circle (18). Since the crank (15) is fitted with connecting rod by the help of the crank pin, the crank also gives rotational movement.

This rotatory movement is utilized in rotating the wheels of a locomotive or rotating the armature of the generator for generating electric power. There are very many other industrial applications, where reciprocating motion of the steam engine is either used directly or converted into rotary motion for obtaining effective work or utilizing power. These steam engines are usually denoted as 'prime movers'.

The branch of engineering which deals with generation of steam and its subsequent utilization in producing either electrical or mechanical power is known as 'Power Plant Engineering'. Let us now try to analyse the differences between various types of reciprocating engines that we have already classified.

(a) *Single acting and double acting*

In a single acting steam engine, as the name suggests, steam acts only on one side of the piston. On the other side of the piston there will be no steam but air at atmospheric pressure. The single acting engines are not used now-a-days.

In a double acting steam engine, steam pressure acts on both sides of the piston. It develops twice the power of a single acting engine.

(b) *Vertical and horizontal engines*

If the engine cylinder is so mounted that its central axis is vertical, the engine is called vertical engine. Conversely, in a horizontal engine, the engine cylinder is mounted with its axis in the horizontal plane. Both these types are common and both are used widely. If placed vertically the engine occupies less floor area. Where the space available is small, it is better to use vertical engines.

(c) *Condensing and non-condensing engines*

In a non-condensing engine the power

developed or work done by steam in the cylinder is less than that in a condensing engine.

The pressure of steam entering the cylinder is nearly equal to the pressure of steam inside the boiler. But the pressure of steam going out of the cylinder is a little above atmospheric pressure in case of a non-condensing engine. In a condensing engine the steam is allowed to exhaust not to atmosphere, but to a chamber called condenser where the pressure is much less than normal atmospheric pressure. That is to say, inside the condenser, we maintain vacuum. This is done to extract more work from the steam.

(d) *Simple or compound engine*

Compound engine has more than one cylinder (two or more). The first cylinder which is known as high pressure cylinder gets the steam at high pressure from the boiler directly. But in this case the steam does not go out to atmosphere or condenser. The exhaust steam from the first cylinder usually goes into the entry side of the second cylinder. This second cylinder is known as low pressure cylinder. Where compound engines consist of more than two cylinders, the first one is known as high pressure cylinder and the last one is known as low pressure cylinder. And the other cylinders are known as intermediate pressure cylinders. Compound engine usually exhausts steam from the last cylinder into a condenser.

Unlike compound engine, a simple engine will allow steam, after it has done the work in the cylinder, to go to atmoshere or to a condenser.

(e) *High speed or low speed engine*

High speed engine or low speed engine is termed on the basis of the rotational speed of the crank. Where the speed is neither very high nor very low, the engine is known as medium speed engine. The speed referred to here indicates the rotary speed of the crankshaft expressed in revolutions per minute. There is no definite line of demarcation between high, medium or low speed. Normally, if the rotary speed of the crankshaft is less than 100 revolutions per minute, we call the engine a slow speed engine. If the crankshaft speed is more than 100 but less than 300 revolutions per minute, we call it a medium speed engine. But high speed engine has a shaft speed of 300 or more revolutions per minute.

Detailed Description

Referring to Fig. 5.2 :

1—Steam engine cylinder
2—Piston
3—Piston rod
4—Crosshead
5—Slide bars or Crosshead guides
6—Connecting rod
7—Crank
8—Driven wheel
9—Eccentric
10—Valve rod operated by eccentric
11—Entering part for steam from boiler
12—Valve chest or steam chest
13—Exit port for steam passing out from the engine cylinder to the atmosphere
14—Slide valve
15—Shaft or wheel àxle
16—Crank pin

With our knowledge just gained about the principle of working of a reciprocating steam engine, we shall now try to understand the principle of working of a steam locomotive.

A complete steam locomotive consists of (i) locomotive boiler, including fire box, (ii) tender for accommodating the driving gadgets, controlling lever operators' cabin, as well as coal bunker and water tank, (iii) steam engines of non-condensing types, and (iv) necessary connection from the piston to the driving wheel, valve displacement mechanism.

Usually a locomotive consists of a number of pairs of wheels, each pair being designated by a particular name. Every pair of carrying wheels is mounted on a shaft known as axle, the distance between the wheels being equal to the distance between the rails on the track (this distance is known as the 'gauge').

Normally, the boiler is mounted on the platform made on the frame. If there are two

cylinders, the cylinders are placed externally on each side of the frame. Steam from the boiler enters into the steam chest and then into the engines through the two branch steam inlet pipes.

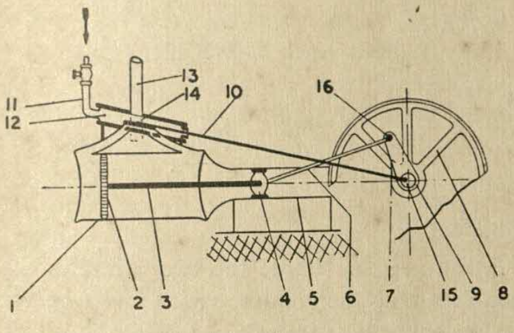


Fig .5.2 *Reciprocating Steam Engine with Link Mechanism for Movement of Slide Valve*

The working principle of the engine is the same as described previously. The simplified sketches drawn in Fig. 5.2 should be helpful. Depending upon the opening of the D-slide valve, which is operated by the valve lever 10, steam enters into the engine and pushes the piston from left to right, until the piston reaches the other end of the cylinder. Uncovering of the right hand side steam port at this stage is accomplished by the shifting of the valve. Fresh steam from the steam chest now enters the cylinder through the right hand side steam port and pushes the piston which moves backwards. This backward motion of the piston from right to left expels the steam, which has already done its work, through the exit opening 13.

This reciprocating motion of the piston is translated into the rotational motion of crank, through crosshead and crank-connecting rod mechanism.

In a locomotive engine the crank is made integral with the wheel, so that the rotation of the crank means rotation of the wheel 8. Though this wheel is driven by the engine, it is called driving wheel in a steam locomotive, because it is the rotation of this wheel that causes the entire locomotive to move on the rails and haul other carriages.

A steam locomotive will normally have a large number of wheels. The wheels can be classified as:

(a) Leading wheels

(b) Powered wheels— $\begin{cases}\text{Driving wheels}\\ \text{Coupled wheels}\end{cases}$

(c) Trailng wheels

If there is another pair of wheels similar in size and shape to 8 (in Fig. 5.2) and if the crank pairs of these two wheels are connected by a rod known as the coupling rod, then these wheels will be known as coupled wheels.

Leading wheels are usually one pair or two pairs of wheels connected by what is known as bogie. These wheels as well as the trailing wheels are much smaller in size. The utility of these wheels is manifold but it is not within our scope of study.

Locomotive engineers will normally specify a locomotive by its wheel arrangement. 'Wheel arrangement' gives only the total number of wheels in the leading, coupling and trailing.

For example, a steam locomotive having wheel arrangement, as shown in Fig. 5.3, will be written as 2-4-2. Similarly the wheel arrangement in Fig. 5.4 will be written as 4-6-2.

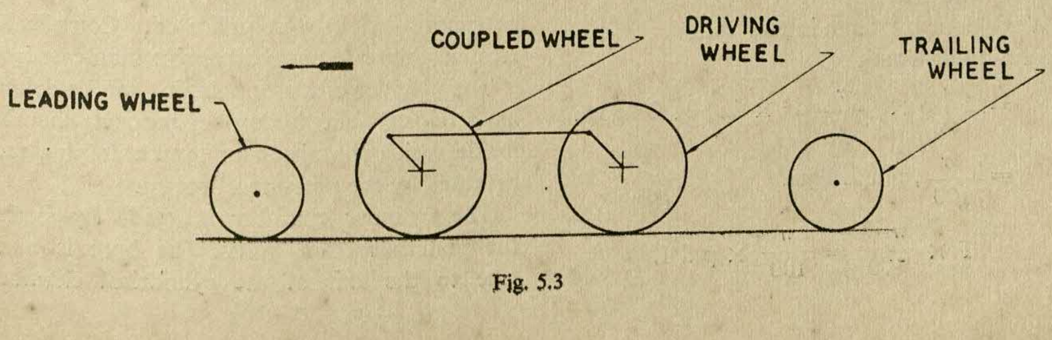


Fig. 5.3

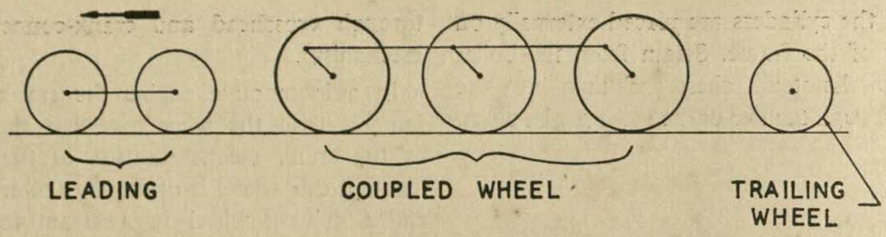


Fig. 5.4

The valve used in the locomotive engine is not a D-slide valve but it is of a piston type. Hence in a locomotive engine the valve is known as a piston valve.

Tractive force of a locomotive

By tractive force of a locomotive we mean the average pull exerted by the locomotive on the train. It is denoted by T in kg. If the driving wheel has the diameter equal to D in cm, then the work done by the tractive force is equal to T $\times$ (circumference of driving wheel)

$$= \frac{T \times \pi D}{100} \text{ kgm.}$$

The work done, thus calculated, is for one revolution of the driving wheel, that is to say, for one revolution of crank. This work done must again be equal to the work done by steam in the locomotive engine cylinder per one revolution of crank.

If

p = mean pressure of steam in the engine cylinder in $\frac{kg}{cm^2}$,

L = stroke of the piston in cm.,

d = diameter of cylinder bore in cm.

Assuming that the locomotive has two cylinders on two sides and that each engine cylinder is double acting,

Work done by steam in two cylinders for one revolution of Crank

$$= 2\left(p \times \frac{\pi}{4} d^2 \times L\right) \times 2 \text{ kgcm.}$$

$$= \frac{\pi}{100}, p\, d^2 L \text{ kgm.}$$

$$T \times \frac{\pi D}{100} = \frac{\pi}{100} \times p\, d^2 L$$

$$\therefore T = \frac{p\, d^2 L}{D}.$$

PROBLEM

Mean pressure inside the two cylinders of a double acting locomotive engine is 10 kg/cm^2. Diameter of the cylinder bore is 40 cm and stroke of the piston is 60 cm. Driving wheels of the locomotive have diameter equal to 225 cm. Find out the tractive force of the locomotive in kg.

SOLUTION

Given

D = 225 cm.

d = 40 cm and L = 60 cm.

p = 10 kg/cm^2

$$T = \frac{10 \times 40^2 \times 60}{225} = \frac{1600 \times 600}{225}$$

=4256 kg.

Cylinder

The most important part of a steam engine is the cylinder. The cylinder is normally made of cast iron. But now-a-days many locomotive cylinders are made of cast steel. Because in most engines the cylinder and the steam jacket are made into one unit (i.e., integral) the shape becomes obviously complicated. Complicated steel castings are more expensive than cast iron.

The cylinder of a steam engine can be defined as a closed but hollow cylindrical chamber inside which the piston or moveable plug reciprocates by the pressure of steam.

The cylinder chamber is made by boring the materials from inside. The bore is made true to the axis of the cylindrical chamber.

The steam chest or the valve box is connected to the cylinder bore on both sides by two curved passages. These passages are known as steam ports. Through these passages steam passes from the valve box to the cylinder or from the cylinder to the valve box. In between the two steam ports is provided another port which is connected to the outside atmosphere. This is known as an exhaust port. In the case of a condensing engine, the exhaust port is connected directly to the condenser where vacuum is always maintained. Work done in a condensing engine is higher than in a non-condensing engine.

It is not within the scope of this book to deal at length with the working of condensing engine or its relative advantages. The exhaust passage is connected with either side of the steam engine cylinder depending upon the directional movement of the valve in the valve box.

The piston while reciprocating inside the barrel of the cylinder is continuously rubbing the barrel surface. As a result, the internal surface of the cylinder gets worn out. But since the cylinder is an expensive object, it is not always practicable to replace the entire cylinder casting. Hence a liner is sometimes fitted inside the cylinder bore. This liner is fitted by applying hydraulic pressure. Inside the liner there is a cylindrical bore. In this bore, the piston moves in close running fit. After a little use, some amount of steam may be condensed into water. This water, which cannot otherwise get out, settles at the bottom of the cylinder bore. To drain out this condensed steam or water, there are usually two drain-off valves, which can be manually operated by one lever and its connecting mechanism.

Piston

The piston ranks second in importance. The part that moves to and fro, that is, forward and backward in an engine cylinder, is known as a piston. The movement of the piston is obviously caused by the pressure of steam acting on its face area.

The piston is usually made of either cast iron or cast steel or forged steel. The piston made of forged or cast steel is lighter in weight than that made of cast iron.

The details of the construction of a piston have been elaborated in Figs. 5.5, 5.6 and 5.7.

Since a piston can be considered as a moveable plug, at any position inside the cylinder it must divide the cylinder space into two steam-tight compartments. That is to say, no steam should pass over the piston from one side to another. But to have them absolutely steam-tight is almost impossible. So the loss of steam over

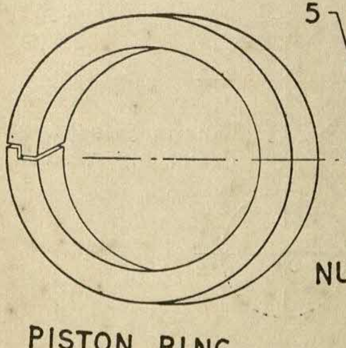


Fig. 5.5

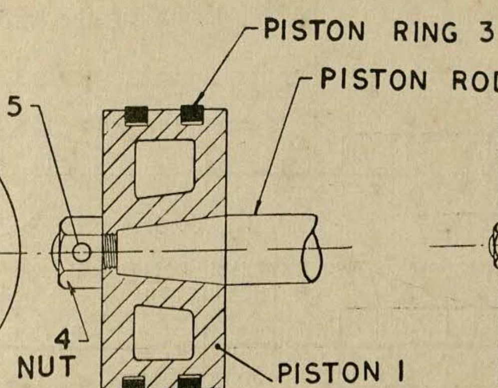


Fig. 5.6

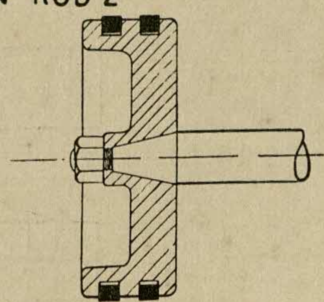


Fig. 5.7

the piston from one side of the cylinder to another is kept to the minimum. This is done by providing piston rings (marked 3 in Fig. 5.6.). The piston rings are made of steel of square cross-section (10mm × 10 mm or 20 mm × 20 mm or any suitable cross-section) formed into a circular ring with a transverse cut, in order to obtain springing effect. There are usually a number of piston rings instead of one. (*see* Fig. 5.5).

The end of the piston rod on which the piston is mounted, is tapered. That is to say, the diameter of the piston rod is gradually reduced. This end fits into the tapered hole of the piston. At the extreme end the piston rod is made into screw thread. After mounting the piston on the piston rod it is fixed by nut. To prevent the nut from coming out, there is a locating pin 5. (*see* Figs. 5.6 and 5.7).

The friction between the piston ring and the inner diameter of the cylinder is not much. It is only sufficient to make the steam tight. That is to say, the piston should not allow the steam inside the cylinder to pass from the working side to the back side. The side of the piston face on which steam acts is known as the working side, while the other side is the back side. But in double acting steam engine the back side becomes the working side in backward motion of the piston.

A simple sketch of the piston ring has been shown in Fig. 5.5.

Internal movement of the piston inside the cylinder bore from one end of the cylinder to the other is known as 'Stroke length' of the cylinder. (*see* Fig. 5.8.) This is equal to twice the length of the crank arm (measured between the centre of crank pin to the centre of the flywheel).

The space inside the cylinder can be divided into three distinct compartments, viz.,

(a) Clearance space in the front end, where there is accumulated steam from previous operation. It is because of this space that the piston cannot come right up to the cylinder cover and strike against it.

(b) Working space. It is the space covered by the length of the stroke or piston movement. This is equal to $\frac{\pi}{4} D^2L$ in volume.

(c) Clearance space in the rear end of the cylinder.

Usually the total clearance space is expressed as a fraction of the working space (say, .05, 0.15).

The total of the spaces mentioned in (a), (b) and (c), that is, the total internal volume of the cylinder, gives what is known as the capacity of the engine cylinder.

Knowing the diameter of the cylinder bore, length of the stroke, we can calculate the

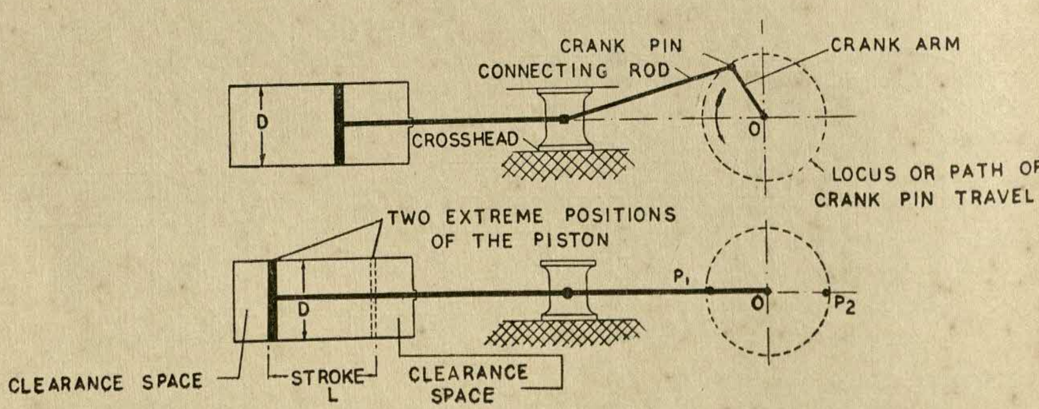


Fig. 5.8

effective volume of the cylinder. From this we can arrive at the cylinder capacity.

cylinder capacity = effective volume + clearance volume. The solution of a problem will illustrate this point easily.

PROBLEM

A steam engine has the internal diameter of the cylinder 600 mm and stroke 800 mm. The clearance volume is approximately 10 per cent of the effective volume. Find out the capacity of the cylinder.

SOLUTION

cylinder capacity = effective volume + clearance volume.

If the effective voume $= V$,
then cylinder capacity $= V + 0.10\ V = 1.10\ V$.

But $V = \frac{\pi}{4} \times 600^2 \times 800$ cu. mm.

$\therefore$ cylinder capacity $= 1.10 \times 0.7854 \times 360000 \times 800$ cu.mm.

The effective volume as dealt with in this problem is equivalent to the speed swept through by the piston in each stroke. Average speed of reciprocation of piston varies from 80 to 250 metres per minute. In some cases of high speed engine the piston speed may rise up to 400 metres/min.

Crosshead

The outer end of the piston rod fits into a part, known as crosshead. The crosshead is connected, in turn, to the connecting rod with the help of a specially shaped pin, called the gudgeon pin. There are numerous types of designs for crosshead. But the principle of working and the constructional features can be well understood from Fig. 5.9.

The main body of the crosshead 1 is made of steel casting. The crosshead slides between the guides 4 known as slide bars. To prevent sideward tilting, the crosshead is also provided with two guide blocks 5. The outer end of the piston rod 2 is lowered in diameter (and slightly tapered in some caes). It gets into the hole of the leading hub 7 of the crosshead. Then the piston rod end is fixed with the help of a cotter 3.

The small end of the connecting rod is fitted with the crosshead with the help of a conical headed pin known as gudgeon pin 6. From Fig. 5.10 it is evident that when the crank is rotating in the direction of the arrow, there are three different forces acting on the crosshead. These forces are:

(1) Forward force on the piston rod P in the direction shown in the figure.
(2) Vertical reaction R of the guide on the crosshead.
(3) Force Q in the connecting rod shown in direction by the arrow in the figure.

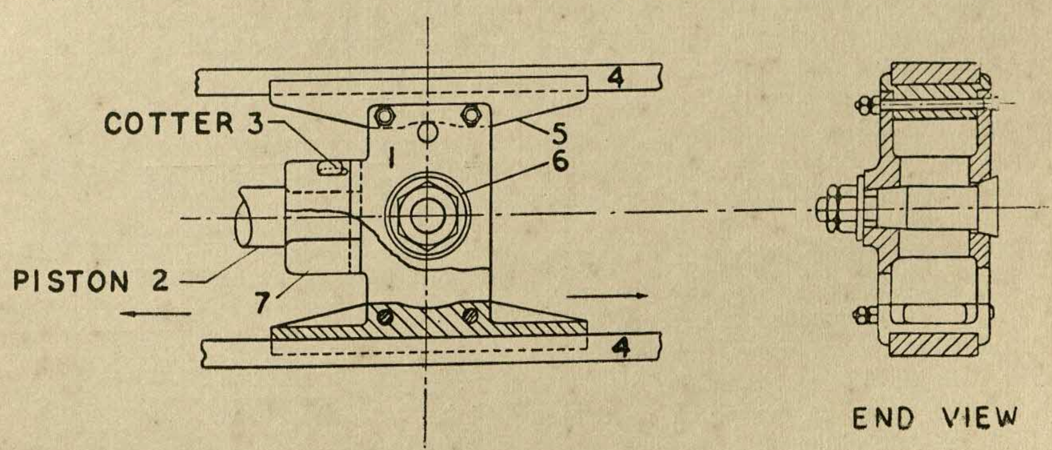


Fig. 5.9

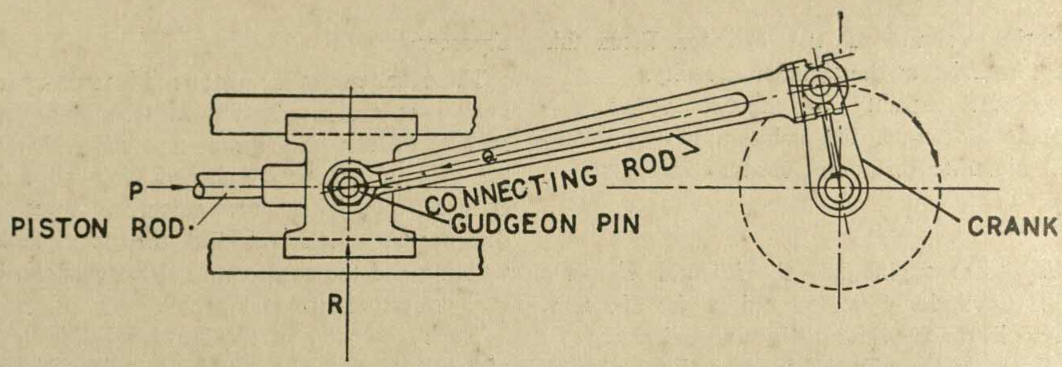


Fig. 5.10

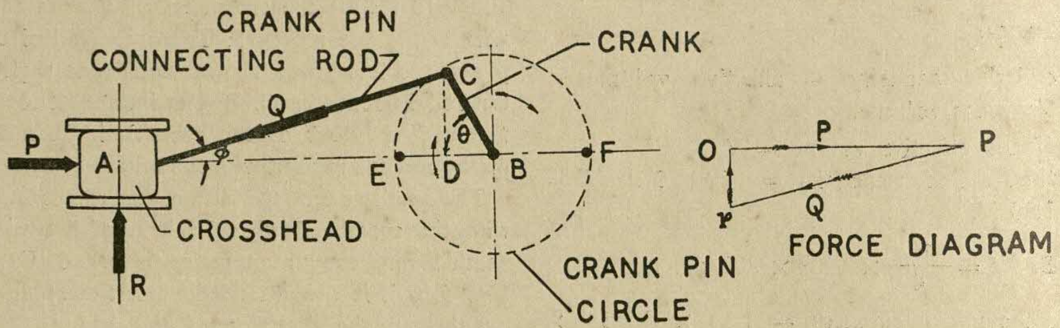


Fig. 5.11

Assuming any particular position denoted by angle, as shown in Fig. 5.11, we can find out the relative magnitude and direction of the forces.

Fig. 5.11 shows the position when the crank makes an angle θ from the point E (E is known as inner dead centre, while F is outer dead centre), and the connecting rod makes an angle θ. The magnitude and direction of the forces can be obtained by constructing the force diagram.

Draw a line OP to measure the magnitude of the piston force P. From P draw Pr parallel to the connecting rod and drop a perpendicular from O to meet at r.

OP represents magnitude and direction of P;
Pr represents magnitude and direction of Q;
rO represents magnitude and direction of R.

P, the force on the piston rod, is usually known. It is equal to the pressure of steam in the cylinder acting on the piston multiplied by the area of the piston.

From the force diagram we can say that

$R = P \tan \phi$ and $Q = \frac{P}{\cos \phi}$. In the figure, BC is the crank, CA is the connecting rod and CD is the perpendicular on the line joining the line AB.

From our basic trigonometric knowledge we know that

$$CD = CB \sin \theta = AC \sin \phi.$$

$$\therefore \sin \phi = \frac{CB}{AC} \times \sin \theta$$

$$= \left(\frac{\text{Length of crank}}{\text{Length of connecting rod}}\right) \times \sin \theta = m. \sin \theta$$

where m is the ratio of crank to connecting rod.

Knowing $\sin \phi$, we can find out the value of $\cos \phi$

$$\cos \phi = \sqrt{1 - m^2 \sin^2 \theta}.$$

$$\therefore R = P \times \frac{m \sin \theta}{\sqrt{1 - m^2 \sin^2 \theta}}$$

$$\text{and } Q = \frac{P}{\sqrt{1 - m^2 \sin^2 \theta}}$$

PROBLEM

The pressure of steam inside the engine cylinder is 5 kg/Cm^2 and the diameter of the piston is 50 cm.

Find the reaction of the guide and the force in the connecting rod, when the crank makes an angle of 30° from the inner dead centre. The ratio of crank length to the length of the connecting rod is $\frac{1}{4}$.

SOLUTION

Given: Pressure in the cylinder = 5 kg/cm^2

Diameter of the piston = 50 cm

$\theta = 30°$.

m = 1/4

P = pressure in the cylinder × Area of the piston

$$= 5 \times (\frac{\pi}{4} \times 50^2) = 9817 \text{ kg.}$$

$\sin \phi = m \sin \theta = 1/4 \times \sin 30° = 0.125$

$\cos \phi = 1—.125^2 = 0.99$

$\tan \phi = 0.12$

$R = P \tan \phi = 9817 \times .12 = 1178$ kg

$$Q = \frac{P}{\cos \phi} = \frac{9817}{0.99} = 9820 \text{ kg}$$

Connecting Rod

Connecting rod connects the crosshead with the crank pin. That is to say, it is connected on one side with the piston through the crosshead, while its other end is fitted on the crank pin. Through the connecting rod, therefore, the reciprocating motion of the piston is transformed into the rotatory motion of the crank pin.

Length of the connecting rod means the length measured between the centre of the gudgeon pin and the centre of the crank pin. Length of the crank similarly means the length equal to radius of the crank pin circle (as shown in Fig. 5.9).

Stroke of an engine = 2 × length of the crank and the length of the crank bears a constant ratio to the length of the connecting rod denoted by 'm'.

Value of 'm' varies between 4 and 6.

In Fig. 5.9 has been shown a typical sketch of an engine connecting rod. Connecting rods can be made from forged steel, either having solid rectangular cross-section or I shaped cross-section. The end of the connecting rod which is fitted to the crosshead is the small end of the connecting rod, while its bigger end is the rear end having connection with the crank pin.

Crank

Crank can be defined as a metallic arm or a bracket having two bosses at its end (*see* Fig. 5.12). These two bosses are made to hold rigidly the crank pin and the crankshaft respectively; it is a necessary part of the engine assembly for transforming the reciprocating motion to rotating motion. The crank is fitted on the crankshaft usually by heating the same. Due to heat the hole in the crank undergoes thermal expansion in diameter and becomes slightly bigger than the crankshaft diameter. Under this hot condition the crank is mounted on the crankshaft. Then the assembly is allowed to cool. As cooling is done, the hole in the crank recovers from its thermal expansion and the crank sits tight and shrunk on the crankshaft. Of course in many cases instead of heating, the assembling is done by applying hydraulic pressure. To make sure that the crank does not rotate on the crankshaft, a key is provided as in Fig. 5.12. Crankshaft of a stationary steam engine is usually mounted between bearings.

Flywheel

The force, acting on the crank pin at any position of the stroke (piston), can be resolved into two components, viz., (i) tangential component, and (ii) radial component. The magnitudes of these two components of the force acting on the crank pin vary during every revolution. During some part of the revolution, the steam is doing more work than what is just necessary, and

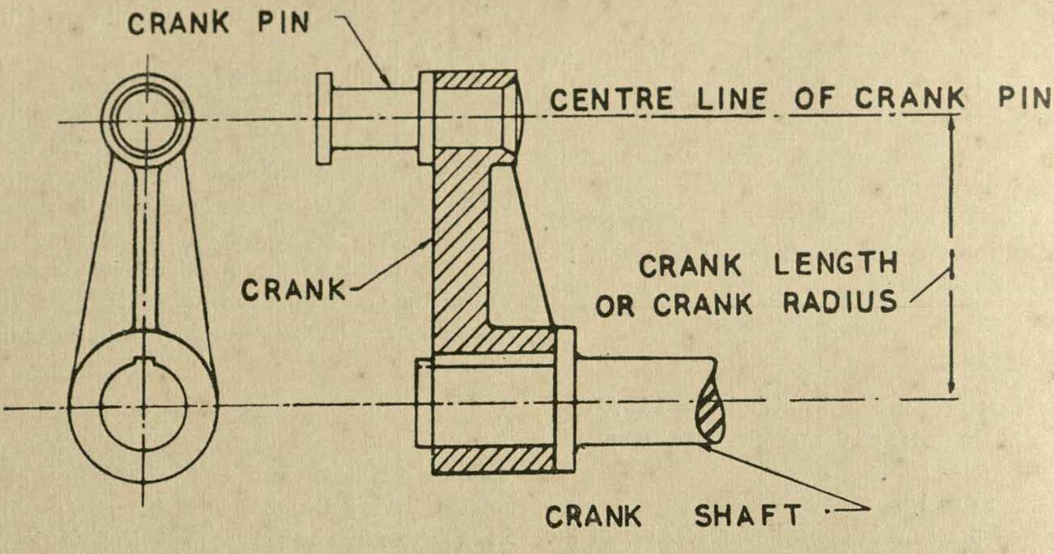


Fig. 5.12 *Cranks and Crankshaft*

during other part of the revolution steam is doing less amount of work. The main function of a flywheel is to release additional energy during that part of the revolution when the work done by steam is less. This is achieved by a fluctuation of speed of the flywheel.

CHAPTER 6

Elementary working of steam turbines and water turbines; internal combustion engines: two-stroke and four-stroke petrol and diesel engines.

6.1 Introduction

In a steam turbine it is the kinetic energy of steam and not the static pressure that is converted into useful work. But in a steam engine it is the static pressure of the steam that causes the piston to reciprocate. This is the essential difference between a reciprocating engine and a turbine. Otherwise, both are used for producing power. The working fluid in a turbine can be steam, water or gas. Accordingly, the turbine can be steam turbine, water turbine or gas turbine.

In the first part of the chapter only the elementary principles of working of a steam turbine and a water turbine have been dealt with; The remaining part of the chapter is devoted to the elementary working of internal combustion engines.

6.2 Steam Turbines

The essential function of a steam turbine is to convert the thermal energy of steam into effective mechanical work. In achieving this objective, the turbine utilizes the kinetic energy of the steam. But in reciprocating steam engines, it is the static pressure of steam and not the kinetic energy that plays an important part. Thus, we say, that in a turbine the action of steam is dynamic, but in a reciprocating engine the action of steam is merely a static one.

The steam generated in the boiler has a certain amount of heat energy known as 'total heat' and denoted by H where H is expressed in B.T.U. or C.H.U. Since in turbine we are using the kinetic energy of the steam, the heat energy of the steam has to be converted into kinetic energy before the steam can enter into the turbine. This conversion of total heat into kinetic energy may be done in one stage or in a number of stages, depending upon the type and design of the turbine.

A turbine usually has two main parts, viz.,

(i) Nozzle or guide, and

(ii) Rotor or moving element.

Nozzle or guide is the stationary element of the turbine in which the heat energy of steam is converted into kinetic energy. This kinetic energy is subsequently utilized in the moving element. The stationary elements and the moving elements (in case there are more than one pair) are usually placed alternatively, so that the steam, doing its mechanical work in a particular moving element, gains in kinetic energy in the immediately preceding stationary element. The rotor of the moving element is mounted on the turbine shaft. This shaft is located in bearings and provided with coupling for transmitting power to any required unit. The rotor is either in the shape of a disc or in the shape of a wheel. This wheel carries a number of blades or buckets. The blades are arranged all around the periphery of the wheel. The steam from the nozzle impinges on these blades or buckets. The impulse thus obtained on the blades causes the rotor to rotate.

In this arrangement, as shown in Fig. 6.1, the steam enters into the nozzle at high pressure and undergoes a considerable amount of pressure drop while passing through the nozzle. There is a fall in thermal energy during this operation, but such a drop is transformed into high velocity (kinetic) energy. The nozzle is so shaped that steam, on passing through it, gains in kinetic energy. Since the rotor, containing a large number of blades having a specific shape, is mounted permanently on the shaft and the shaft is located between bearings, the rotor rotates with a high velocity of rotation, as the jet of steam coming out of the nozzle impinges on the blades. There may be a series of nozzles instead of one. Casing is sealed around the turbine shaft by gland packing. This prevents the leakage of steam from casing to atmosphere, but does not cause any obstruction to the rotation of the shaft along with the rotor. This type of turbine, where the steam undergoes pressure drop only in the nozzle (and not while passing through blades), is known as an 'Impulse Turbine'.

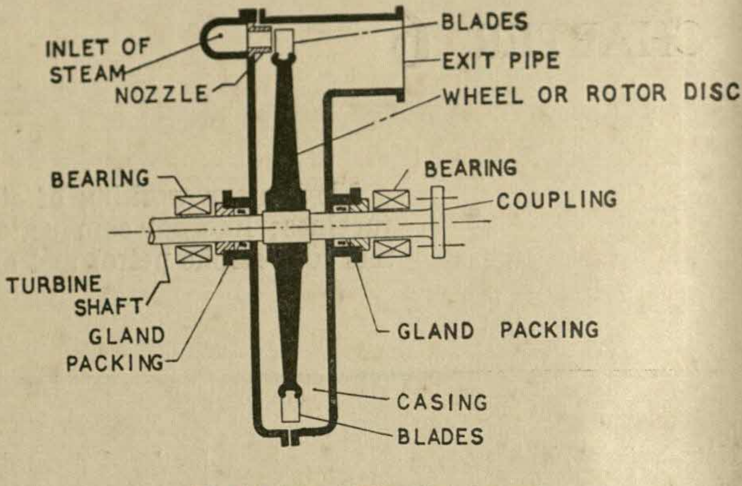


Fig. 6.1 *Steam Turbine (Impulse type)*

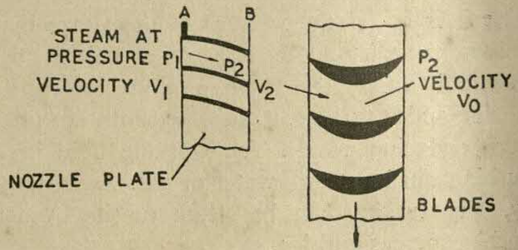


Fig. 6.2 (a). *Impulse Turbine*

But there is another type of turbine, where pressure drop takes place partly in the nozzle and partly while passing through the blades. Such a type goes by the name 'Reaction Turbine'.

These can be represented by the skeleton diagrams in Fig. 6.2 (a) and (b).

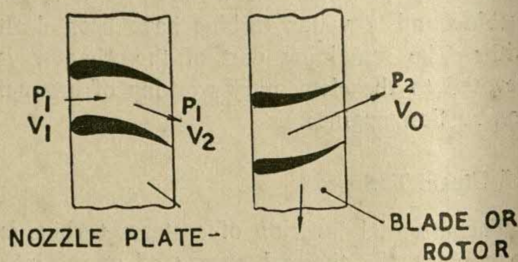


Fig. 6.2 (b) *Reaction Turbine*

Essential Difference between Impulse and Reaction Turbines

In Fig. 6.2 (a), it can be seen that the steam entering the nozzle has a pressure P_1 (High value) and a velocity V_1 (which is very small as compared to V_2). On leaving the nozzle the pressure of the steam falls from P_1 to P_2 but velocity increases from V_1 to V_2. This steam passes through the blades. Its pressure remains the same even after passing through the blades, but its velocity changes from V_2 to V_0. Change in velocity from V_2 to V_0 causes a change in the momentum of the steam and it is this change that causes the rotation of the wheel containing the blades. But in Fig. 6.2 (b), which shows

the principle of action of a reaction turbine, there is a drop in pressure from P_1 to P^1 in the nozzle and there is a further drop in pressure while passing through the blades. This pressure drop is from P^1 to P_2. Thus in a reaction type of steam turbine, the total pressure drop, which is converted into kinetic energy, distributes itself between the nozzle and the blades, i.e., between the stationary and moving units.

It should always be remembered that the steam while passing through the nozzle does no mechanical work; hence the total energy of steam at the entry to the nozzle must equal the total energy at exit from the nozzle. Steam enters the nozzle with a certain velocity V_1 but this V_1 is nothing in comparison to V_2, the velocity with which steam emerges from the nozzle. In practice V_1 is not even one hundredth of V_2. Hence for all calculation purposes V_1 is neglected altogether.

6.3 Turbine Work

The output work which we get from the turbine shaft is not equal to the work done by the steam while passing through the blades. It is always less than the work done by the steam. This is because (i) certain amount of work done by the steam is lost in overcoming static inertia of the empty blades and (ii) the casing containing the rotor always remains full of steam and hence a further amount of work done by steam is lost due to the friction of the rotor rotating in the casing steam.

All these losses reappear in the form of heat but this heat is carried away by the exhaust steam.

6.4 Water Turbines

Let us suppose that in Fig. 6.3, a certain amount of water is kept in a tank at a height of H_0 measured from the centre line, taken across the pipe main from which water is being tapped. On opening the tap, water flows through the valve with a certain velocity, and the height H_1 gradually comes down.

Total energy of water can be regarded as a summation of its potential energy, pressure

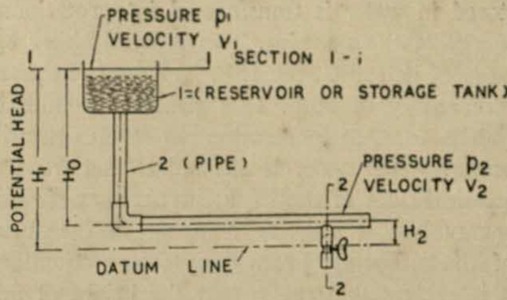


Fig. 6.3

energy and kinetic energy. If there is continuity in the flow of water, as in this case, then at any cross-section taken in its path, the total energy must remain the same.

Kinetic energy per unit weight of water $= \frac{V^2}{2g}$, where V is the velocity of flow at the section considered.

Potential energy per unit weight of water = H, where H is the potential height of water level measured from the datum.

Pressure energy per unit weight of water $= \frac{P}{W}$, where P is the pressure of water at the section considered and W is the specific weight of water.

Thus the total energy of water =

$$E = \frac{V^2}{2g} + \frac{P}{W} + H.$$

If we now consider two cross-sections 1-1 and 2-2 between which there is continuity of water flow, total energy at these cross-sections must not change.

$$\frac{V^2_1}{2g} + \frac{P_1}{W} + H_1 = \frac{V_2^2}{2g} + \frac{P_2}{W} H_2.$$

At the cross-section 1 — 1, $V_1 = 0$, $P_1 =$ atmospheric pressure.

At the cross-section 2—2, water is flowing to atmosphere with velocity V_2 $\therefore$ P_2 = atmospheric pressure.

Thus $P_1 = P_2$., $V_1 = 0$.

$$\therefore \sqrt{2g\,(H_1 - H_2)} = V_2$$

$$\text{or } V_2 = \sqrt{2g\,H_0}$$

In a water turbine, which is also known as 'Hydraulic rotodynamic machine', the energy

stored in water is transformed into rotational energy of the machine. This is done either by a fall of its static head H or by a fall in its pressure energy or both. This principle is utilized widely for the generation of hydro-electric power. When water is allowed to fall from a certain height of the storage tank, its potential energy is lost only to reappear in the form of kinetic energy. From the previous equation, it is evident that the greater the height of fall H_0, the more is the velocity of water at the outlet end. Thus, if at the outlet end we provide a nozzle directing the water on to a series of blades or buckets of a wheel, then the wheel rotates by the reaction of the water forces acting on the bucket. In a water turbine this wheel comprises the impeller of the turbine or rotor of the turbine. Thus the turbine rotates. This rotation of turbine causes the electrical generator to rotate, since the turbine is coupled with the generator. Thus electricity is produced. This is known as hydro-electricity.

The entire installation of the water turbine plant should, therefore, consist of a reservoir for storing water at a considerable height, the turbine chamber, directing nozzle for allowing the water to impinge on the buckets of the water turbine, the suction end from which the water is pumped into the reservoir height and the delivery end from which the water is allowed to flow out.

The working principle will be clear from a look at the two Figs. 6.4 and 6.5. Fig. 6.4 shows the arrangement for rotating a hydraulic wheel by the reaction of the water flowing through it. Fig. 6.5 shows the sketch of a Pelton wheel, which is nothing but a common type of water turbine used in hydro-electricity generation. In the figure are shown (1) Working wheel (Pelton wheel); (2) Buckets or Blades; (3) Directing apparatus or nozzles, including the needle of a Pelton turbine.

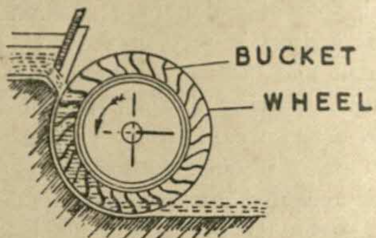


Fig. 6.4 *Hydraulic Wheel*

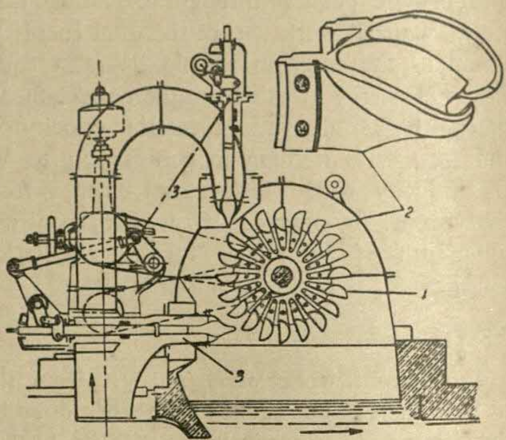


Fig. 6.5 *Pelton Turbine*

6.5 Internal Combustion Engines

Internal combustion engine is a particular variety of heat engine, where the heat necessary for doing mechanical work is produced by burning fuel inside the engine cylinder.

Internal combustion engines can be classified as under:

INTERNAL COMBUSTION ENGINES

- On the basis of fuel
  - Gas Engines
  - Petrol Engines
  - Oil Engines
- On the basis of cycle
  - Four Stroke Cycle
  - Two Stroke Cycle

In gas engines, the usual fuel is coal gas or producer gas. This fuel is mixed with adequate quantity of air to effect complete combustion and is allowed to enter into the cylinder. Inside the cylinder the mixture is ignited with the help of an electric spark.

The various functions of an internal combustion engine can be classified as below:

1. Allowing the charge of air or charge containing a mixture of air and fuel to enter into the cylinder through a suction valve.

2. Compression of the charge inside the cylinder. In case only air is taken in before the compression stroke, an injection of the fuel also takes place.

3. Ignition of the charge.

4. Combustion of the fuel either at constant pressure or at constant volume or under variable pressure and volume.

5. Expansion of the hot gases after combustion takes place inside the cylinder.

6. Exhaust of the used product of combustion.

Petrol engines usually have one of the three fuels, viz., (a) Petrol (b) Petrol + Benzol or (c) Alcohol. The petrol engines are very widely used in automobile or aircraft engines. The fuel is vaporized by passing through a carburettor and then mixed with air. This mixture is sucked into the cylinder in the suction stroke and is allowed to ignite by means of a spark provided by the spark plug.

In the oil engines, the oil is sprayed into the engine cylinder where it is mixed with air and the mixture is ignited by the heat generated by its compression inside the cylinder. Any one of the internal combustion engines described above can work on either a four-stroke cycle or a two-stroke cycle.

All these operations can be performed either during two strokes or during four strokes of the piston. And, accordingly, we get two-stroke cycle engine or four-stroke cycle engine. Here by cycle we mean the number of strokes required to complete the above series of operations.

6.5.1 *Four-Stroke Engine*

The working principle of a four-stroke engine can be explained by a reference to Fig. 6.6 (a), (b), (c) and (d).

In the 1st stroke: the charging of the fuel takes place and hence it is called 'charging stroke'.

In the 2nd stroke: the charge is compressed and ignited. It is called the 'compression stroke'.

In the 3rd stroke: the expansion of hot gases causes the piston to move out in the cylinder. This is known as 'working stroke'.

In the 4th stroke: exhaust of the used products of combustion takes place and hence it is known as the 'exhaust stroke'.

In the first stroke the piston moves outwards by the rotation of the crank. The pressure inside the cylinder falls below atmosphere and the fuel valve opens and the charge gets into the cylinder. This charging continues till the crank moves from position OA to OB. At the position of the crank indicated by OB the fuel valve closes (*see* Fig. 6.5a).

The second stroke starts when the crank is in the position OC, as shown in Fig. 6.5 (b), rotating clockwise and it continues up to the crank position OA. During this stroke the piston moves in compressing the charge inside. The pressure inside the cylinder rises high and the fuel valve and exhaust valve both remain closed.

In the third stroke the valves remain closed. Ignition of charge takes place a little before the completion of the compression stroke. The pressure inside the closed space of the cylinder rises very high due to the high heat generated by the combustion. Due to this high pressure the gases expand and the piston moves outward. This is the only working stroke out of the four strokes. This expansion stroke continues till the piston comes to the extreme right end of the cylinder. But the valve arrangement is made such that the exhaust valve opens a little earlier, at point E in Fig. 6.5 (d), that is, when the crank is in the position OE rotating clockwise. In the fourth stroke the exhaust of the gases takes place due to the piston moving in, that is, from right to left. The exhaust valve remains open, though the fuel valve is closed. This stroke is known as the exhaust stroke of the engine.

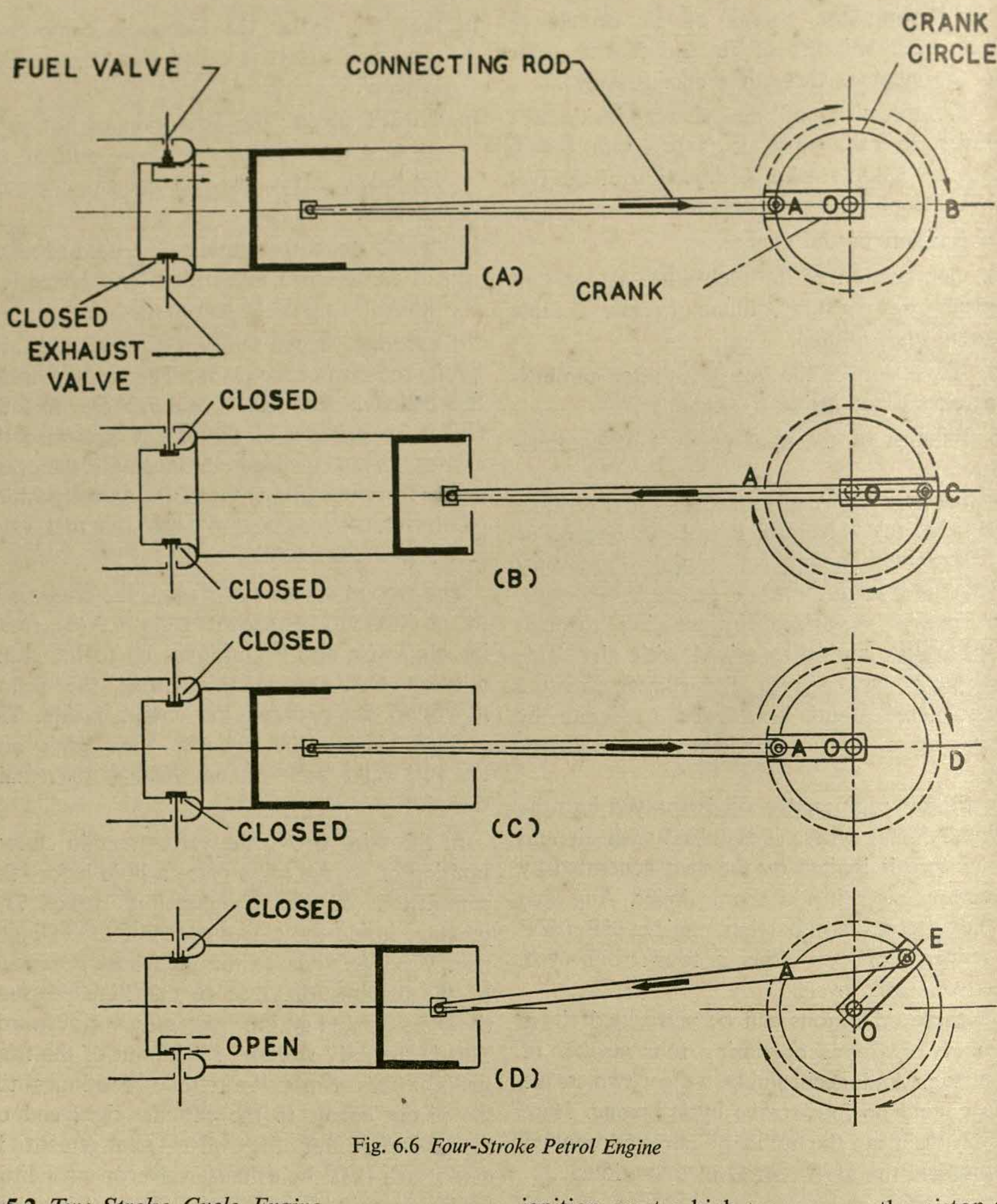


Fig. 6.6 *Four-Stroke Petrol Engine*

6.5.2 *Two-Stroke Cycle Engine*

The principle of working of a two-stroke petrol engine can be easily understood by considering the expansion of the ignited charge first. Fig. 6.7 shows the position of the crank vertically up indicated by OA.

The hot gases of combustion produced by ignition exert a high pressure on the piston and thereby cause it to move downwards. During this operation the crank rotates anti-clockwise. In the case of two-stroke engines, the fuel valve and the exhaust valve are replaced by transfer port and exhaust port respectively. The exhaust port being a little higher up than the transfer port and also owing to the shape of the piston

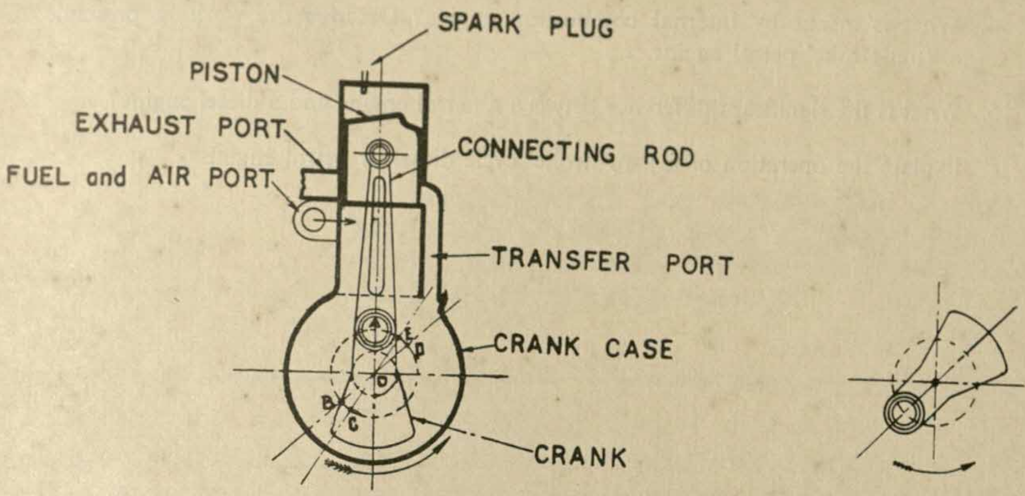


Fig. 6.7 *Two-Stroke Petrol Engine*

crown, the exhaust port opens when the crank reaches the position OB. The burnt gases start escaping into atmosphere. When the crank reaches the position OC, the transfer port opens and the fresh charge of fuel and air starts getting into the cylinder from the crank case through the transfer channel. The exhaust port and the transfer port, from now onwards, remain open. Some amount of the fresh charge is lost in driving out the burnt gases. This is known as 'scavenging'. When the crank reaches the position OD, the inlet of fresh charge ceases, but the exhaust port still remains open. The exhaust port closes when the crank reaches the position OE. The rest of the upward stroke is utilized in compressing the charge. Just before the completion of the compression of the charge, the compressed charge is ignited by electric spark from spark plug. The operations, then, are repeated.

In the case of diesel engine, only air is allowed to get into the cylinder through transfer port, while in petrol engine, as discussed above, a mixture of air and fuel is allowed inside. In the case of diesel engine the spark plug is replaced by fuel injector. Fuel oil is sprayed into the cylinder just before the completion of the compression stroke. The temperature of compression is enough to ignite the charge.

EXERCISES

1. Explain the essential difference between a reciprocating steam engine and a steam turbine.

2. Briefly discuss with a neat sketch the working principle of a steam turbine showing its various parts.

3. Describe with a neat sketch the principle of the working of a water turbine.

4. What is meant by internal combustion engine? Describe the working principle of a 'four-stroke' petrol engine.

5. What is the significant difference between a petrol engine and a diesel engine?

6. Explain the operation of a 'two-stroke' cycle diesel or petrol engine.

CHAPTER 7

Pumps: definition and classification of pumps, description of different types of pumps and their working with particular reference to suction pump, centrifugal pump and gear pump.

7.1 Introduction

Pump can be defined as a machine used for transforming the mechanical energy of the driving source (i.e., input) into the mechanical energy of the fluid it handles.

It can be used for raising fluid through a certain height or displacing a certain portion of the fluid or for obtaining compressed air or gases. Fluids discharged from the pump are usually at a pressure higher than atmospheric.

7.2 Classification

Pumps are classified into three major categories, viz., centrifugal, rotary and reciprocating, depending upon their characteristic features of construction and principle of working.

The comprehensive classification of the various types of pumps used in practice is given below.

PUMPS
- Centrifugal
- Rotary
  - Gear type
  - Vane type
  - Cam and piston type
  - Screw type
- Reciprocating

The classification of pumps into three categories, viz., centrifugal, rotary and reciprocating, is made only to indicate the mechanics of moving the fluids.

Centrifugal pumps operate at a constant speed. In a centrifugal pump there are two principal parts, viz., impeller and a diffuser The liquid, say water, enters the impeller through the central region and passes out through the outer periphery into the diffuser or volute casing. In the diffuser, the velocity energy of the water is progressively reduced. The velocity energy which is reduced appears as static pressurė, so that the final delivery of the water can be obtained at a high static pressure. This static pressure will enable the water to be lifted over a great height.

Rotary and reciprocating pumps are known as positive displacement pumps. In these pumps, the liquid is entrapped and then moved from the inlet end to the outlet end, thereby causing positive displacement. A fuller description of the principle of working has been given later in this chapter.

Usual application of all the pumps mentioned above is in lifting water or any fluid through a certain vertical height, in effecting a steady delivery of liquid at constant quantity or at constant speed, supplying compressed air or gases, supplying boiler feed water and in connection with turbo-machinery.

The principle of working and the constructional features of only a few of the various types of pumps available in practice are explained here.

7.3 Suction Pump

The suction pump is a type of reciprocating pump used widely for raising water from under-

ground or from the bottom of a well. The commonly seen tube-well falls into this category.

The construction and the principle of working of such a pump are very simple. It is usually operated by hand. Fig. 7.1 shows the diagrammatic sketch of a tube-well. The various parts of the pump have been named in the diagram. Such a pump is normally operated by applying manual pressure at the free end of the lever.

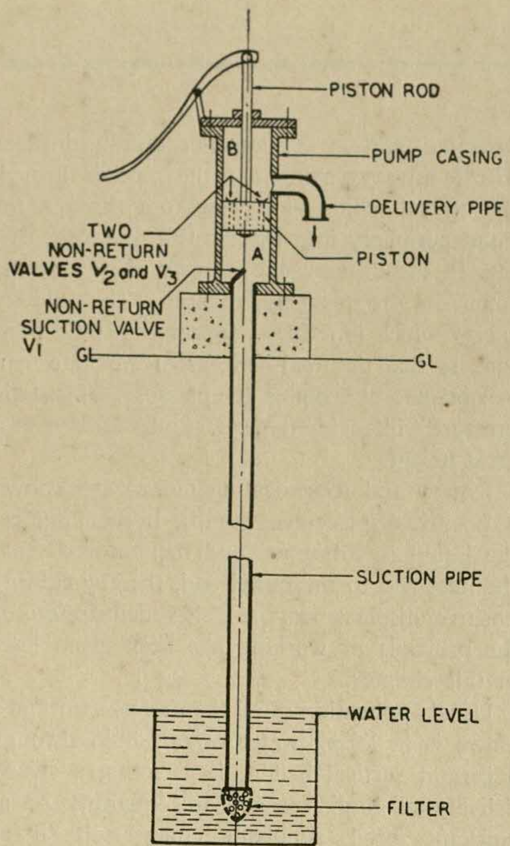


Fig. 7.1

The pump casing is connected to the water level under the ground by the suction pipe. To the bottom end of the suction pipe is fitted a filter. And at the junction of the suction pipe and the pump casing is fitted a non-return valve V_1. This non-return valve is a one-way valve which allows the water to be drawn into the space marked A. But it does not allow the water to recede again to the suction pipe. The spaces A and B are separated by a piston. The piston moves vertically up and down inside the pump casing by applying pressure at the free end of the lever. The movement of the piston is effected with the help of the lever and the piston rod, since the piston is mounted at the end of the piston rod. The spaces A and B are connected with two orifices. These orifices are nothing but openings shown by dotted lines in the piston. The water can go up from space A to space B through these openings. But these openings are fitted at the upper end by two non-return valves V_2 and V_3. Like the valve V_1, these two valves also allow the water to enter into B but it does not allow the water, which has once entered into B, to go back to A. Finally the pumped water is discharged through the delivery pipe. The principle of working is quite easy to understand. Let us assume that at the beginning, the pressure of air inside the delivery pipe, space B, space A and the suction pipe is atmospheric pressure. If we now move the piston up, the pressure inside A falls to a lower value, since the volume of the space A increases. As a result, valve V_1 will open upwards. This allows the water to enter from suction pipe to the space A, since water flows from high pressure to low pressure. But during this period the valves V_2 and V_3 will remain closed, since the pressure in the space B is more than that in space A.

When the piston is moved downwards, the valve V_1, being a non-return valve, will close by the pressure of water in the space A. Since water in the space A cannot go back into the suction pipe, as the piston moves downward it will push open the valves V_2 and V_3. Thus, during the downward movement of the piston, the water will enter into space B.

If the piston is now moved up again, the water in the space B will have no other alternative but to go out through the delivery pipe at a sufficiently high pressure.

The filter fitted at the bottom end of the suction pipe prevents the muddy materials or dirt from getting into the suction pipe.

In this type of pump, the final delivery of water is not continuous but intermittent. Usually this cannot lift water through a very great height.

Suction pump is not an accurate name for this type of pump because in this pump the flow of water is caused by the difference of pressure in the two adjoining spaces and not by any vacuum.

The pressure of the water discharged through the delivery pipe is always above atmospheric, otherwise flow will not take place.

7.4 Reciprocating Pump

A reciprocating pump is nothing but a positive displacement pump, which delivers a definite and fixed quantity of fluid in each stroke of piston that reciprocates inside the cylinder of the pump. It is usually driven by a motor or an engine. It consists of a motion cylinder, piston, piston rod, connecting rod, crank, valves, suction and delivery pipes.

A simple diagrammatic sketch of a reciprocating pump is shown in Fig. 7.2.

The legend connected with the Fig. 7.2 is given below:

1. Cylinder
2. Piston
3. Piston rod
4. Connecting rod
5. Crank
6. Non-return valve at the suction end
7. Non-return valve at the delivery end
8. Suction pipe
9. Suction tank
10. Filter
11. Delivery pipe.

In the sketch shown in Fig. 7.2, the piston 2 reciprocates inside the cylinder 1. This reciprocating motion is obtained by translating the rotational motion of the crank 5 through the connecting rod 4. The non-return valve 6 will only allow the water to enter from the suction pipe to the cylinder, when the pressure

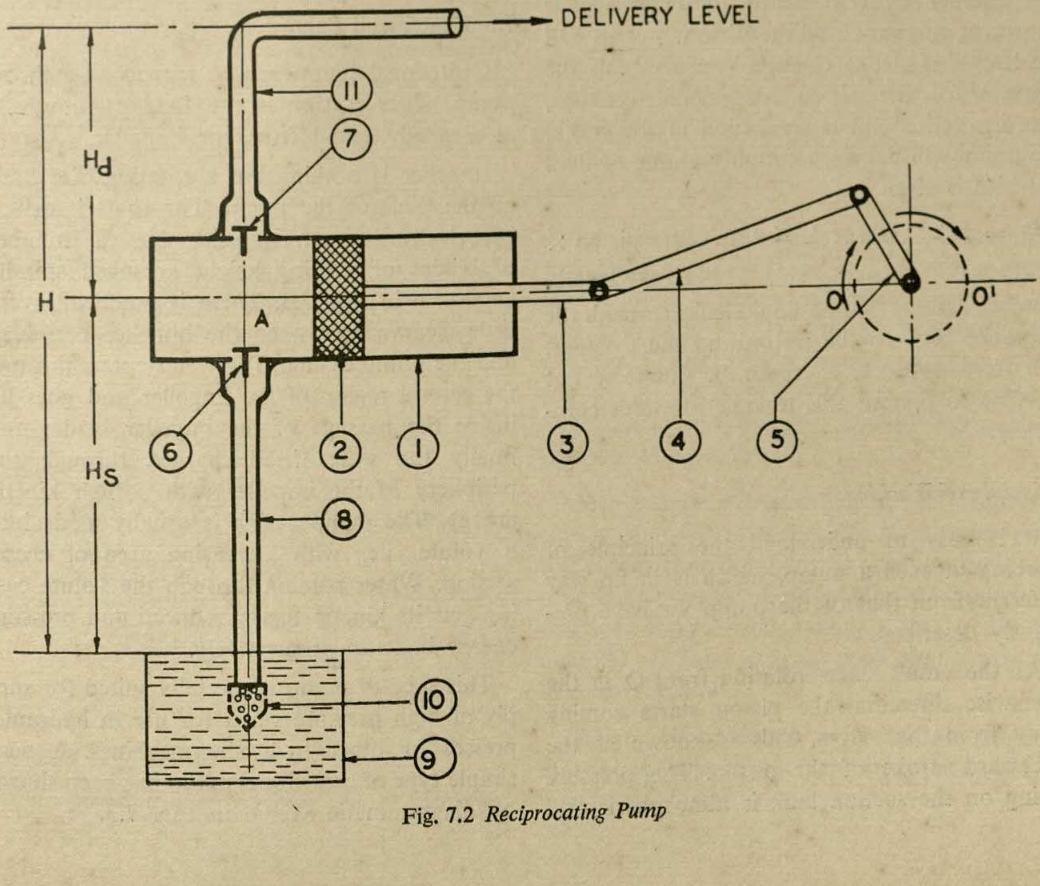


Fig. 7.2 *Reciprocating Pump*

inside the cylinder space A is less than that in the suction pipe 8.

Similarly, the non-return valve 7 will open only to allow the water to pass into the delivery pipe from the cylinder space A. It will never allow the water to return from the delivery pipe to the cylinder space. The distance between the delivery level and the centre line of the piston is termed as the delivery head. It is indicated in the diagram by H_d. Similarly, the distance between the centre line of the piston and the level of water in the suction tank is known as suction head. It is indicated in the diagram by H_s. The total height through which the water is lifted is given as H, where $H = H_d + H_s$.

The purpose of the filter fitted to the bottom end of the suction pipe under the water level of the suction tank is to sort out any mud or dirt that may be present with the water. The length through which the piston traverses inside the cylinder either forward or backward is known as the stroke of the piston. Let us call the length of stroke of the piston as L. If the diameter of the piston is designated as D, then in each complete revolution of the crank, the pump will deliver a certain volume of fluid Q which is given by

$$Q = \frac{\pi}{4} \cdot D^2 \times L = \text{Area of the piston} \times \text{stroke length}.$$

Here we assume that no liquid leaks through the clearance between the piston and the cylinder, i.e., from space A to space B. But it is not possible to prevent this leakage of water completely.

Principle of Working

It is easy to understand the principle of working of such a pump, which is in no way different from that of the pump we have previously described.

As the crank starts rotating from O in the clockwise direction, the piston starts coming away from the valves. This is known as the backward stroke of the piston. The pressure acting on the suction tank is atmospheric and as the piston starts its backward stroke the pressure inside the space A falls below atmospheric. This results in the opening of the non-return valve at the suction end of the cylinder and the water gets into the cylinder and fills the space A. During this stroke, the non-return valve at the delivery end of the cylinder will be closed due to the atmospheric pressure in the delivery pipe. The backward stroke will last till the crank reaches O^1. As the crank advances further from O^1 to O in the clockwise direction, the piston begins its forward stroke. In the forward stroke the pressure of water in the cylinder space will make the valve 6 close but the valve 7 will open outwards. Opening of the valve 7 will mean the escape of water from the cylinder to the delivery pipe. It is only during the forward stroke that the water is discharged from the delivery end, and hence the discharge in this case is intermittent.

7.5 Centrifugal Pump

Centrifugal pump can be named as a throw pump, since it throws the fluid continuously at a steady speed from the impeller.

Impeller is nothing but a rotating disc fixed on the shaft of the pump. The shaft is driven by electric motor. Impeller has a number of blades of varying height arranged spirally as shown in Fig. 7.3. There is practically very little clearance between the impeller periphery and the pump casing. The water enters through the central region of the impeller and goes up inside the passage of the impeller blades and finally the water is discharged through the periphery of the impeller with a high kinetic energy. The pump casing is usually made into a volute, i.e., with increasing area of cross-section. Water passing through the volute casing gets its kinetic energy reduced and pressure energy built up progressively.

This type of pump is specially suited for supply of high pressure water for use in hydraulic presses or other hydraulic machines. A very simple type of centrifugal pump has been shown by diagrammatic sketch in Fig. 7.3.

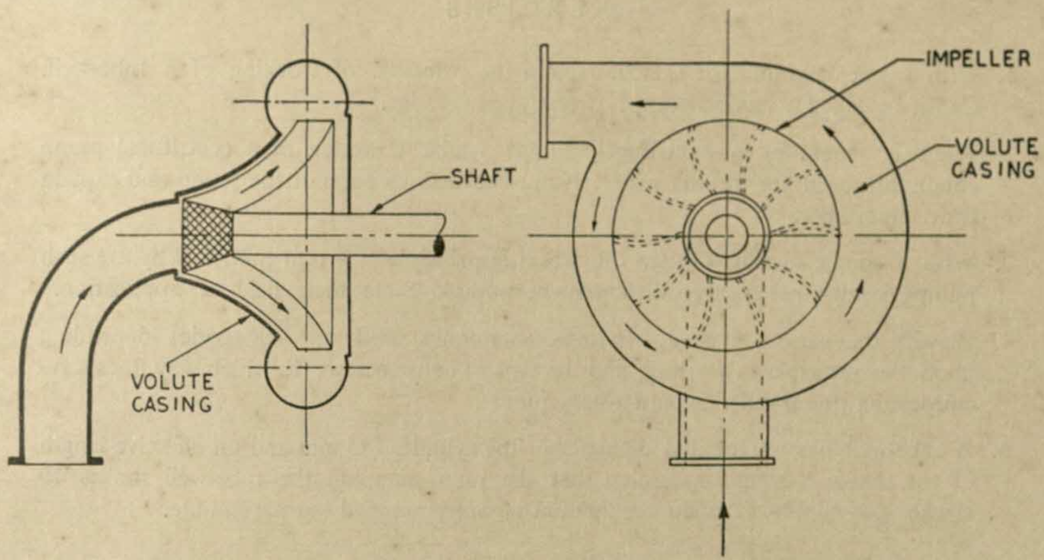


Fig. 7.3 *Centrifugal Pump*

7.6 Gear Pump

Gear pump is the simplest variety of the rotary pump. The essential parts of a gear pump are the following:

1—Gear Pump casing

2—3—Spur gears

4 and 5— Gear shaft i.e., shaft on which the gears are mounted. These shafts are driven by the electric motor in such a way that the gears are driven perfectly mated with each other. Typical sketch of a gear pump is shown in Fig. 7.4.

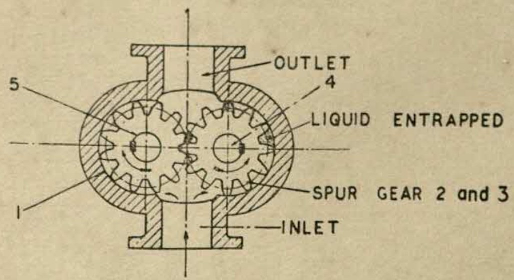


Fig. 7.4 *Gear Pump*

Principle of Working

The principle of working is as follows. The water or oil enters through the inlet end into the gear case. The gears may be spur gears or single or double helical gears. In between the outside diameter of the gear and the casing there should be ideally no clearance. But in practice there is a very small clearance.

The fluid on entering through the inlet gets entrapped between the casing and the space between the successive teeth as shown in the sketch in Fig. 7.4, and the gears rotate. This entrapped water is carried away to the outlet end and is delivered. Only one gear is driven by motor driven shaft, and the other gear plays the part of an idler.

Gear pumps are used in all oil hydraulic circuit of machine tools. The fluid handled in this case is usually oil having very low compressible characteristic. Gear pumps are known as positive displacement pumps, since a definite quantity of fluid is entrapped and displaced to cause the flow.

Unlike a reciprocating pump, the rotary pump, of whatever type it may be, discharges a smooth flow of the fluid.

EXERCISES

1. With a neat diagrammatic sketch, explain the principle of working of a tube-well. Can it be called a suction pump? If not, state reasons.

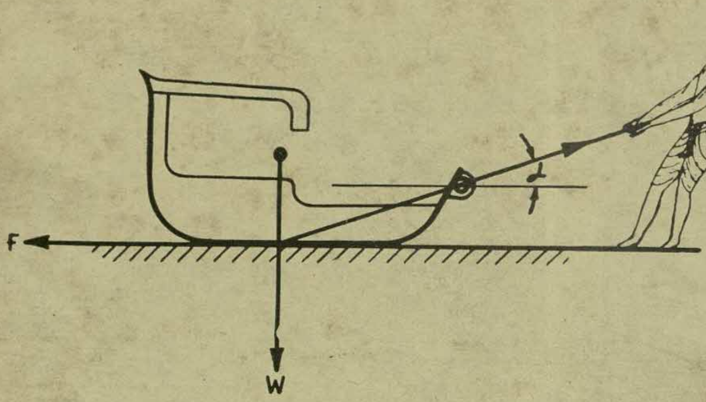
2. What is meant by a centrifugal pump? Make a sketch of a centrifugal pump commonly used for raising water. Name the various parts of the pump and explain their importance.

3. With a simple sketch, explain the working principle of a gear pump. Why are such pumps known as positive displacement pumps? State their field of application.

4. Classify the various types of pumps commonly used into categories depending upon the principle of working and the type of construction. In which way does a reciprocating pump differ from a rotary pump?

5. A tube-well has an internal diameter of the cylinder 125 mm and an effective length of the stroke 200 mm. Assuming that the man pumping the tube-well makes 10 strokes per minute, calculate the amount of water pumped out per minute.

   [*Answer*: Area of the cylinder $= \frac{\pi}{4} \times (12.5)^2 = 122.76\ cm^2$. Volume of the cylinder $=$ $122.76 \times 20 = 2455.2\ cm^3$. Since the pump is making 10 strokes/min, the total volume of water pumped out per minute$=24552\ cm^3$/min.
   This is equivalent to 24.552 litres/min.]



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